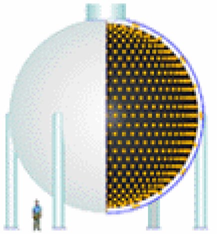

The Fermilab Neutrino Program – Status and Challenges Ahead

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*with acknowledgements to everyone who leaves talks where I can find them

Preface

- The turn-on of the LHC in ~2007 will mark the end of the Fermilab Tevatron's unprecedented 20+ year reign as the world's highest energy collider.
- With the cancellation of the BTeV (B physics) project, the collider program is scheduled to be terminated in 2009, possibly sooner.
- The lab has a strong commitment to the International Linear Collider, but physics results are at least 15 years away.
- -> Neutrino physics will be the centerpiece of Fermilab science for at least a decade.

Luckily, neutrinos are very interesting

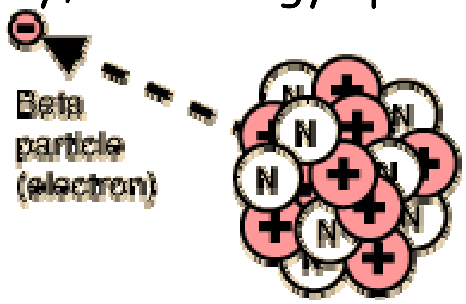
- Many unanswered questions
  - Type: Dirac vs. Majorana
  - Generations: 3 active, but possibly sterile
  - Masses and mass differences
  - Mixing angles
  - CP and possibly even CPT violation
- Multi-disciplinary
  - Study
    - Solar
    - Atmospheric
    - Reactor
    - Lab based (beta-decay)
    - Accelerator Based
  - Application
    - Particle physics
    - Astrophysics
    - Cosmology
- Trying to coordinate the effort and priorities
  - See "APS Multidivisional Neutino Study"
    - http://www.aps.org/neutino/

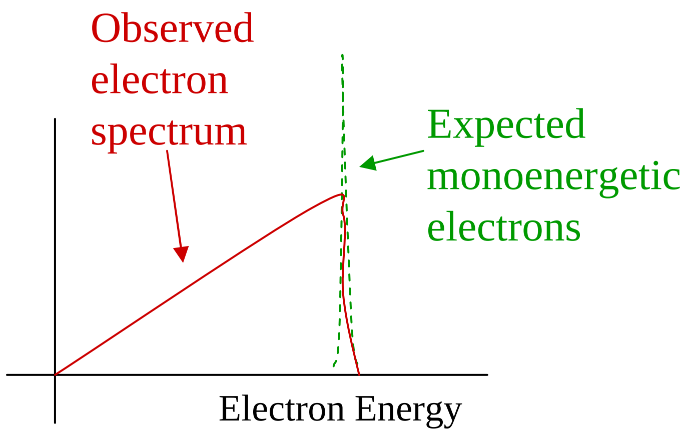
This Talk

- **A Brief History of Neutrinos**
  - Background
  - Neutrino “problem”
  - Neutrino oscillations
- **Some Key Experimental Results**
  - SuperKamiokande
  - SNO
  - Reactor Summary
  - K2K
  - LSND (????)
  - Where do we stand?
- **Major Fermilab Experiments**
  - MiniBooNE
  - NuMI/Minos
  - Nova
- **Meeting the Needs of these Experiments**
  - Existing Complex
  - Post-Collider
  - Longer Term

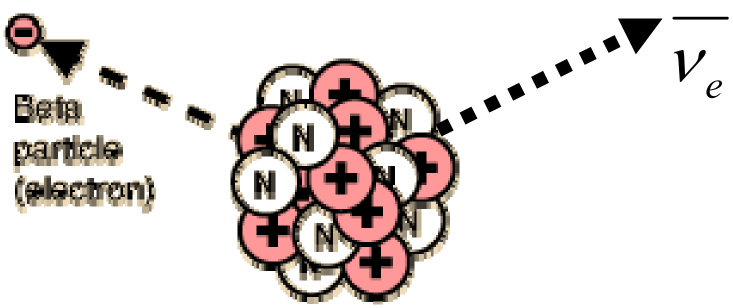
A Brief History of Neutrinos: The Beginning

In "beta decay", one element changes to another when the nucleus emits an electron (or positron). Looked like a 2-body decay, but energy spectrum wrong.





In 1930, Wolfgang Pauli suggested a *"desperate remedy"*, in which an "invisible" particle was carrying away the missing energy. He called this particle a "neutron".



Enrico Fermi changed the name to "neutrino" in 1933, and it became an integral part of his **extremely successful** weak decay theory.

In 1956, Reines and Cowen observe first direct evidence of neutrinos – 26 years after their prediction!

The Question of Mass, the Standard Model

- All observed kinematics of neutrino interactions are consistent with **zero mass** to within the limits of sensitivity.
- In Fermi model (and later Standard Model), neutrinos are massless *by definition*.
- In 1956, Bruno Pontecorvo first shows that it might be possible for neutrinos to *oscillate* from one type to another if they have a small – **but nonzero** – mass.

Other important developments:

- 1962: Lederman, Steinberger, and Schwartz show that that there are at least two distinct "flavors" of neutrinos ($\nu_\mu \neq \nu_e$)
- 1970's: "Standard Model" completed – with *massless* neutrinos.
- 1989: LEP experiments prove there are **only three flavors** of active neutrino (ν_e ,ν_μ, and ν_τ)

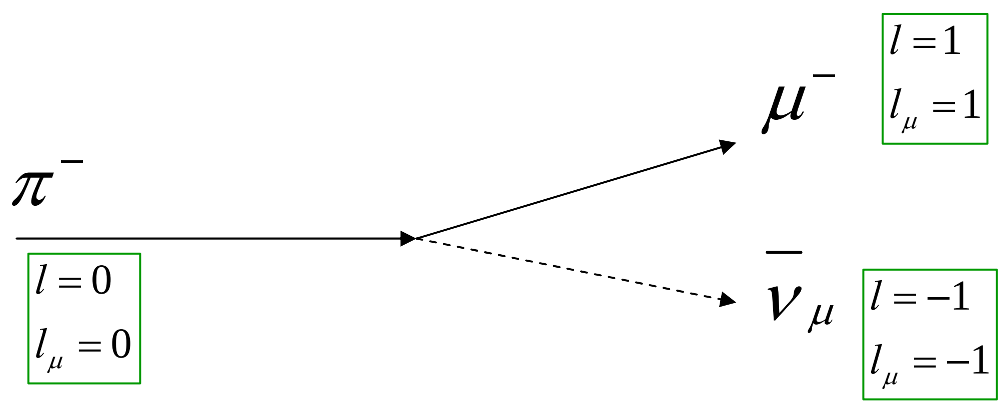
Neutrinos in the Standard Model

Each Generation lepton has an associated neutrino

$$\begin{pmatrix} e^- \\ \updownarrow \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \updownarrow \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \updownarrow \\ \nu_\tau \end{pmatrix}$$

The weak interaction causes a charged lepton to "flip" to a neutrino and vice versa

The weak interaction conserves "lepton number"



The “Neutrino Problem”

- 1968: Experiment in the Homestake Mine first observes neutrinos from the Sun, **but there are far fewer than predicted.** Possibilities:
  - Experiment wrong?
  - Solar Model wrong? *(⇐ believed by most not involved)*
  - Enough created, but maybe oscillated (or decayed to something else) along the way.
- ~1987: Also appeared to be too few atmospheric muon neutrinos. Less uncertainty in prediction. Similar explanation.
- Both results confirmed by numerous experiments over the years.
- 1998: SuperKamiokande observes clear oscillatory behavior in signals from atmospheric neutrinos. For most, this establishes neutrino oscillations “beyond a reasonable doubt”.

Neutrino Oscillations

- Neutrinos are produced as *weak eigenstates* (ν_e ,ν_μ, or ν_τ).
- In general, these can be represented as *linear combination of mass eigenstates*.
- If the above matrix is not diagonal *and* the masses are not equal, then the net weak flavor content will *oscillate* as the neutrinos propagate.
- **Example:** if there is mixing between the ν_e and ν_μ:

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\text{Flavor eigenstates}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{Mass eigenstates}}$$

then the probability that a ν_e will be detected as a ν_μ after a distance *L* is:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27 \bullet \Delta m^2 \bullet \frac{L}{E}\right)$$

Distance in *km*

Energy in GeV

$\boxed{m_2^2 - m_1^2 \text{ (in eV}^2\text{)}}$

Only measure *magnitude* of the *difference* of the square of the masses!

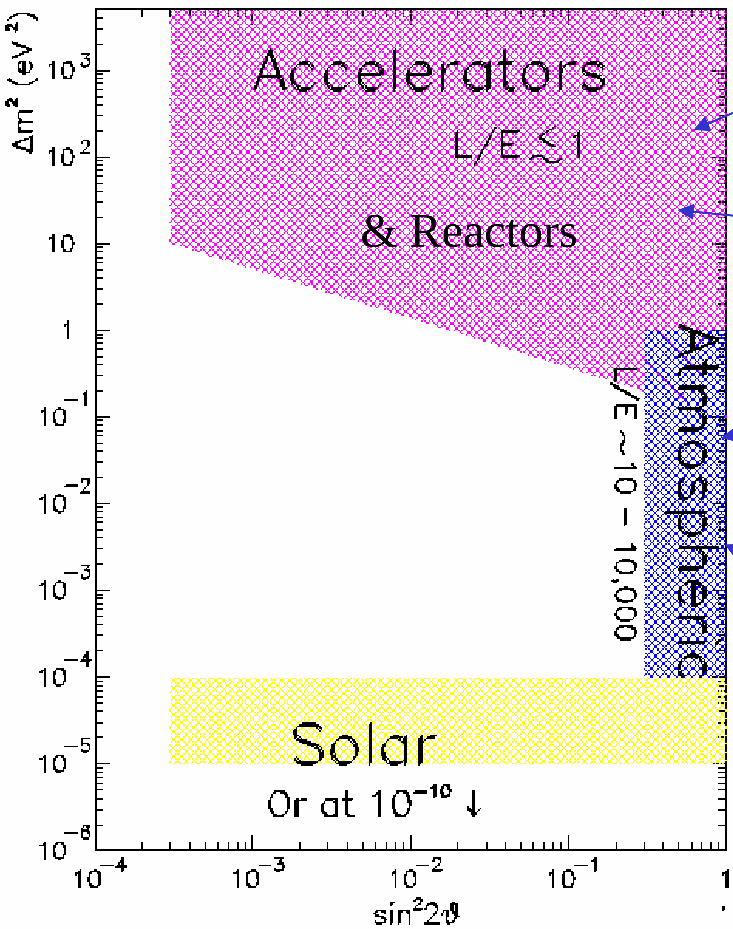
Problem: need a heck of a lot of neutrinos to study this!

Sources of a Heck of a Lot of Neutrinos

- The sun:
  - Mechanism: nuclear reactions
  - Pros: free
  - Cons: only electron neutrinos, low energy, exact flux hard to calculate, can't turn it on and off.
- Atmosphere:
  - Mechanism: Cosmic rays make pions, which decay to muons, electrons, and neutrinos.
  - Pros: free, muon and electron neutrinos, higher energy than solar neutrinos, flux easier to calculate.
  - Cons: flux fairly low, can't turn it on and off.
- Nuclear Reactors:
  - Mechanism: nuclear reactions.
  - Pros: "free", they do go on and off.
  - Cons: only electron neutrinos, low energy, little control of on and off cycles.
- Accelerators:
  - Mechanism: beam dumps -> particle decays + shielding -> neutrinos
  - Pros: Can get all flavors of neutrinos, higher energy, can control source.
  - Cons: NOT free

Probing Neutrino Mass Differences

Different experiments probe different ranges of $\frac{L}{E}$ ← Path length, ← Energy



Accelerators use π decay to *directly* probe $\nu_\mu \to \nu_e$

Reactors use use *disappearance* to probe $\nu_e \to ?$

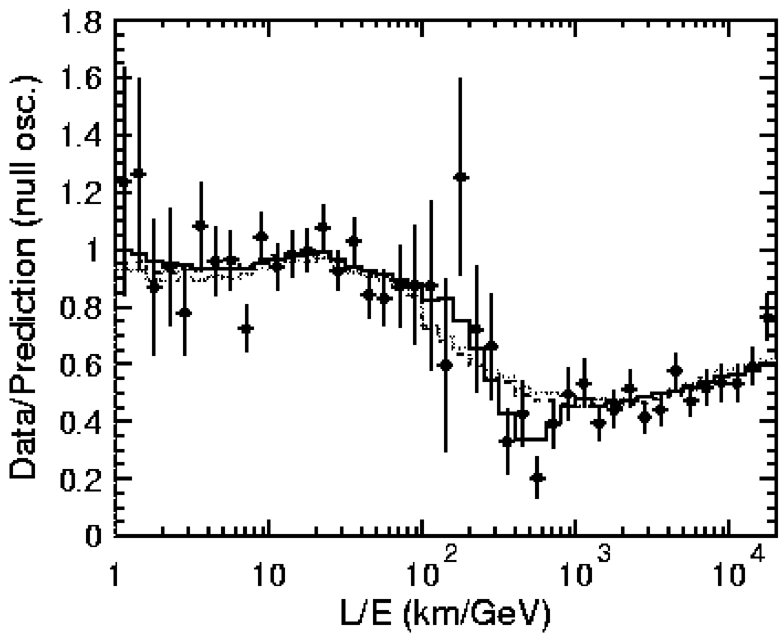
Cerenkov detectors directly measure ν_μ and ν_e content in atmospheric neutrinos. Fit to $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$ mixing hypotheses

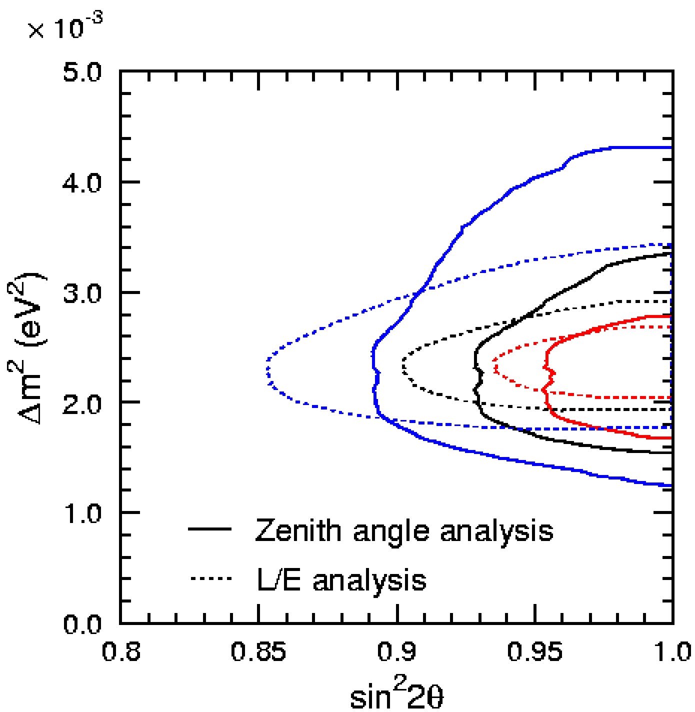
Also probe with "long baseline" accelerator experiments

Solar neutrino experiments typically measure the disappearance of ν_e.

SuperKamiokande Atmospheric Result

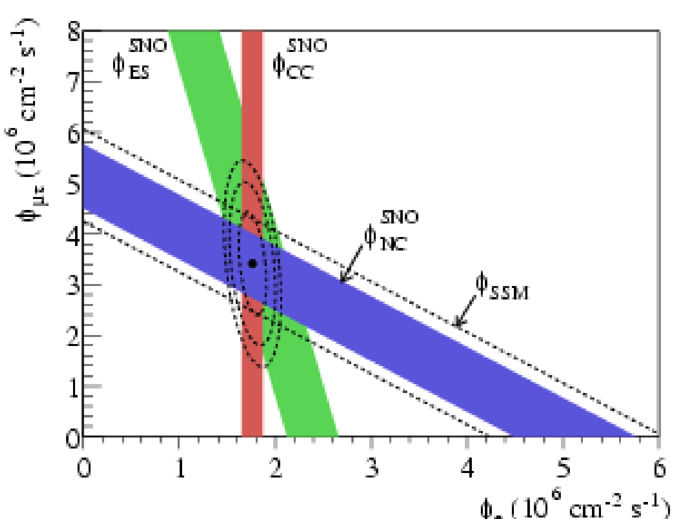
- Huge water Cerenkov detector can directly measure ν_μ and ν_e signals.
- Use azimuthal dependence to measure distance traveled (through the Earth)
- Positive result announced in 1998.
- Consistent with $\nu_\mu \leftrightarrow \nu_\tau$ mixing.

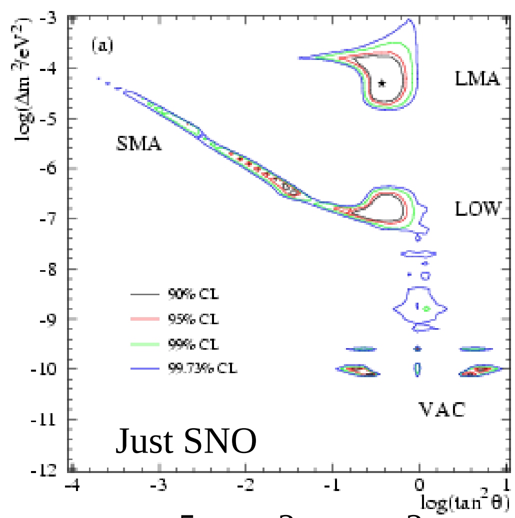


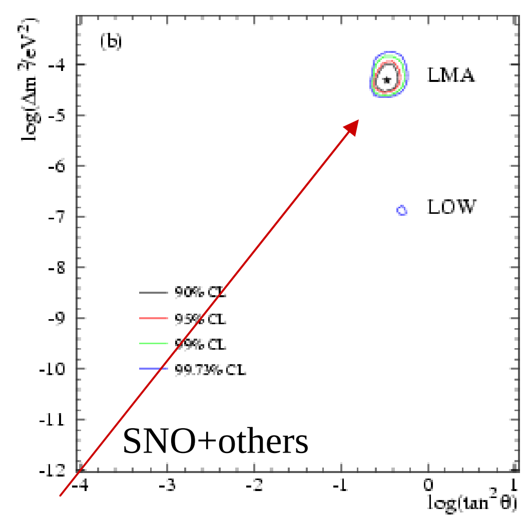


SNO Solar Neutrino Result

- Looked for Cerenkov signals in a large detector filled with heavy water.
- Focus on ^{8}B neutrinos
- Used 3 reactions:
  - $\nu_e + d \rightarrow p + p + e^-$: only sensitive to ν_e
  - $\nu_x + d \rightarrow p + n + \nu_x$: equally sensitive to ν_e, ν_μ, ν_τ
  - $\nu_x + e^- \rightarrow \nu_x + e^-$: 6 times more sensitive to ν_e than ν_μ, ν_τ *d*
- Consistent with initial full SSM flux of ν_e's mixing to ν_μ, ν_τ



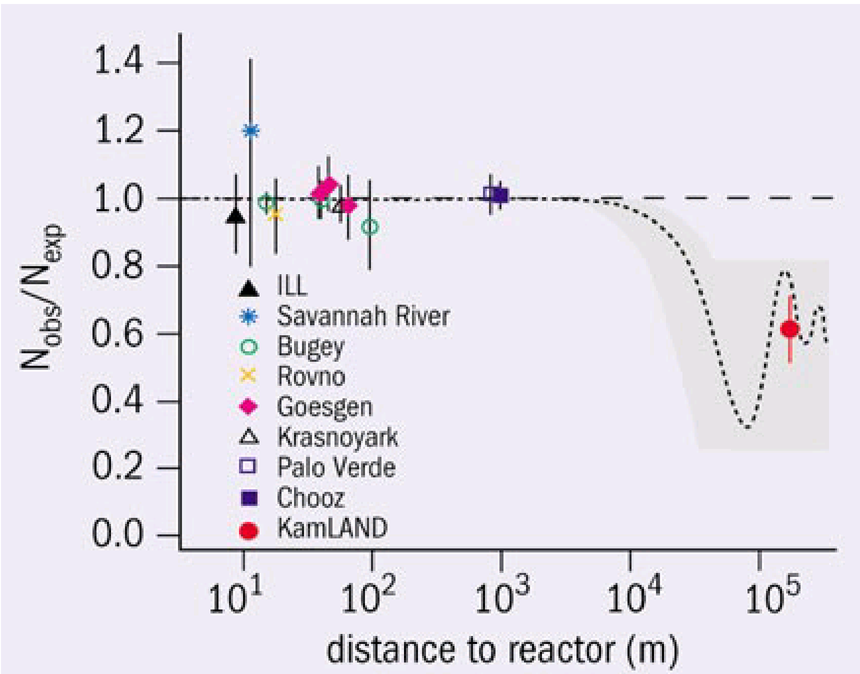


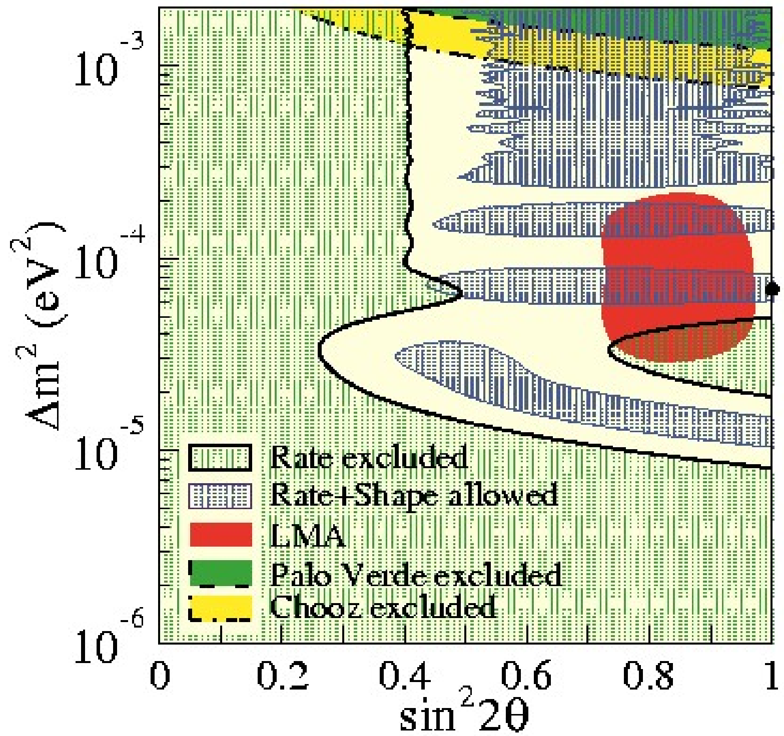


$$\mathrm{Favor:}\ \Delta m^2 \approx 5\times10^{-5}\,\mathrm{eV}^2;\ \tan^2\theta \approx .34$$

Reactor Experimental Results

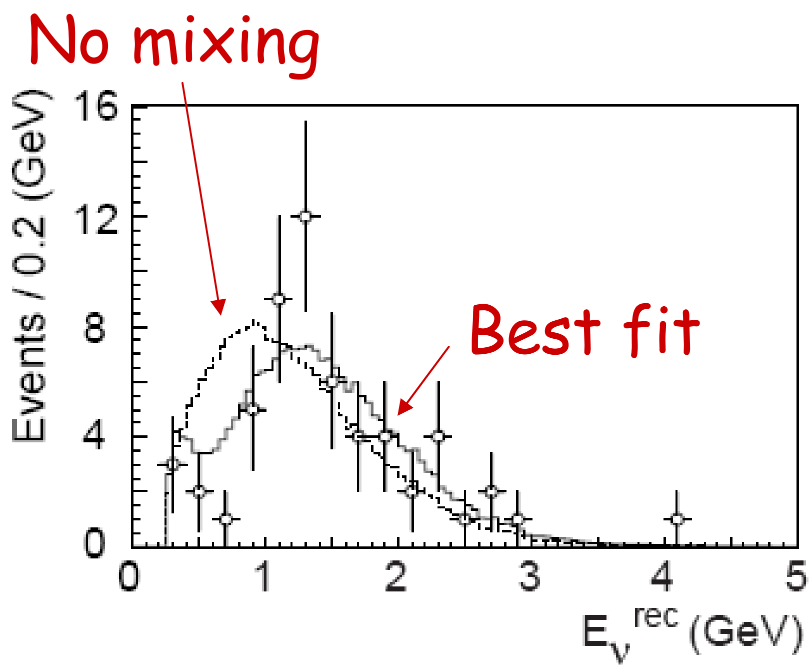
- Single reactor experiments (Chooz, Bugey, etc). Look for ν_e disappearance: all negative
- KamLAND (single scintillator detector looking at ALL Japanese reactors): ν_e disappearance consistent with mixing.

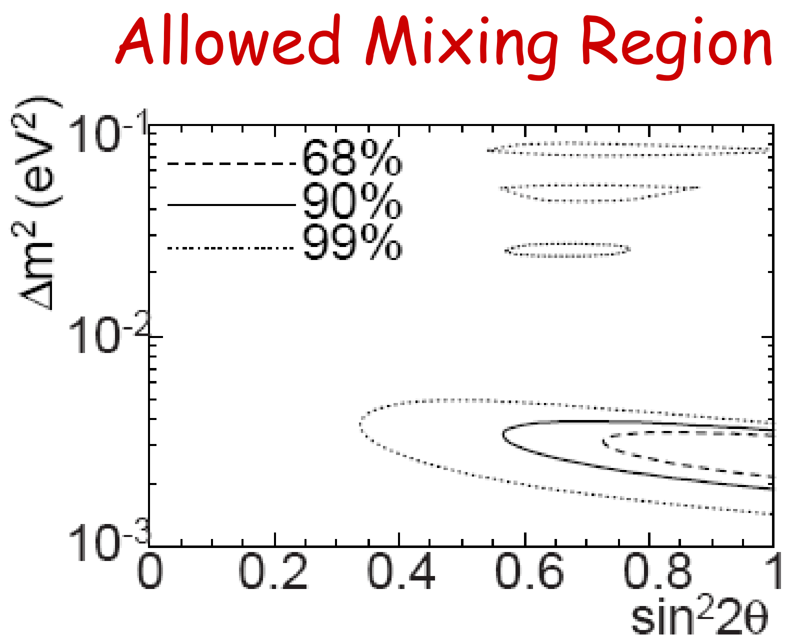




K2K

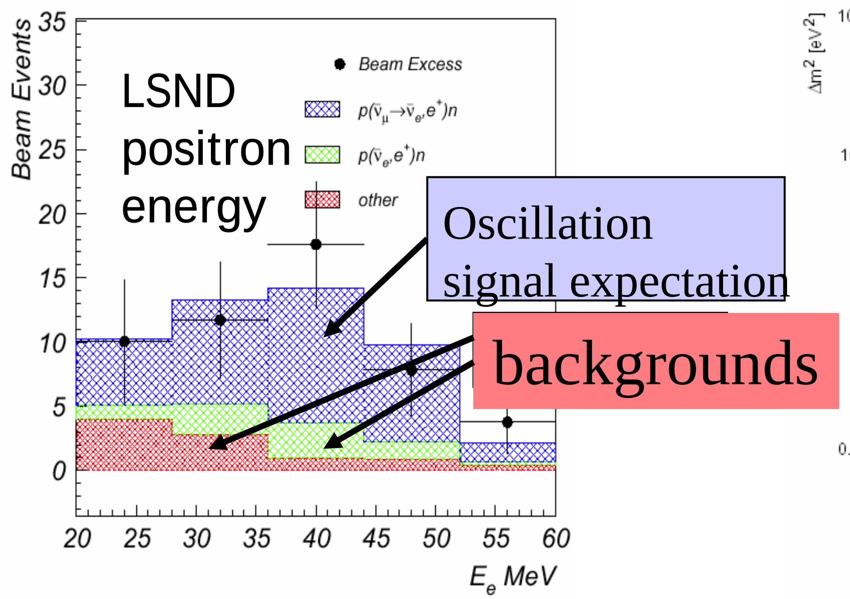
- First "long baseline Experiment
  - Beam from KEK PS to Kamiokande, 250 km away
  - Look for nm disappearance (atmospheric "problem")
  - Results consistent with mixing

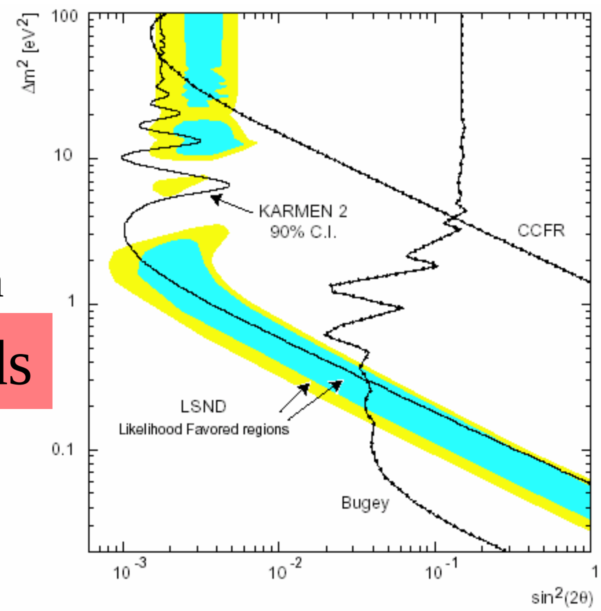




LSND Experiment (odd man out)

- Looked for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in π decay from the 800 MeV LANSCE proton beam at Los Alamos
  - Look for $\bar{\nu}_e$ appearance via: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Look for ν_e appearance via: $\nu_e + C \rightarrow e^- + X$
- Observe excess in both channels (higher significance in $\bar{\nu}_e$)
- Only exclusive *appearance* result to date.
- Doesn't fit "nicely" with the other results!





$$\Delta m^2 \approx .05 - 1\,\mathrm{eV}^2$$

Full Mixing Picture (without LSND)

- General Mixing Parameterization

CP violating phase

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

QUARKS

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

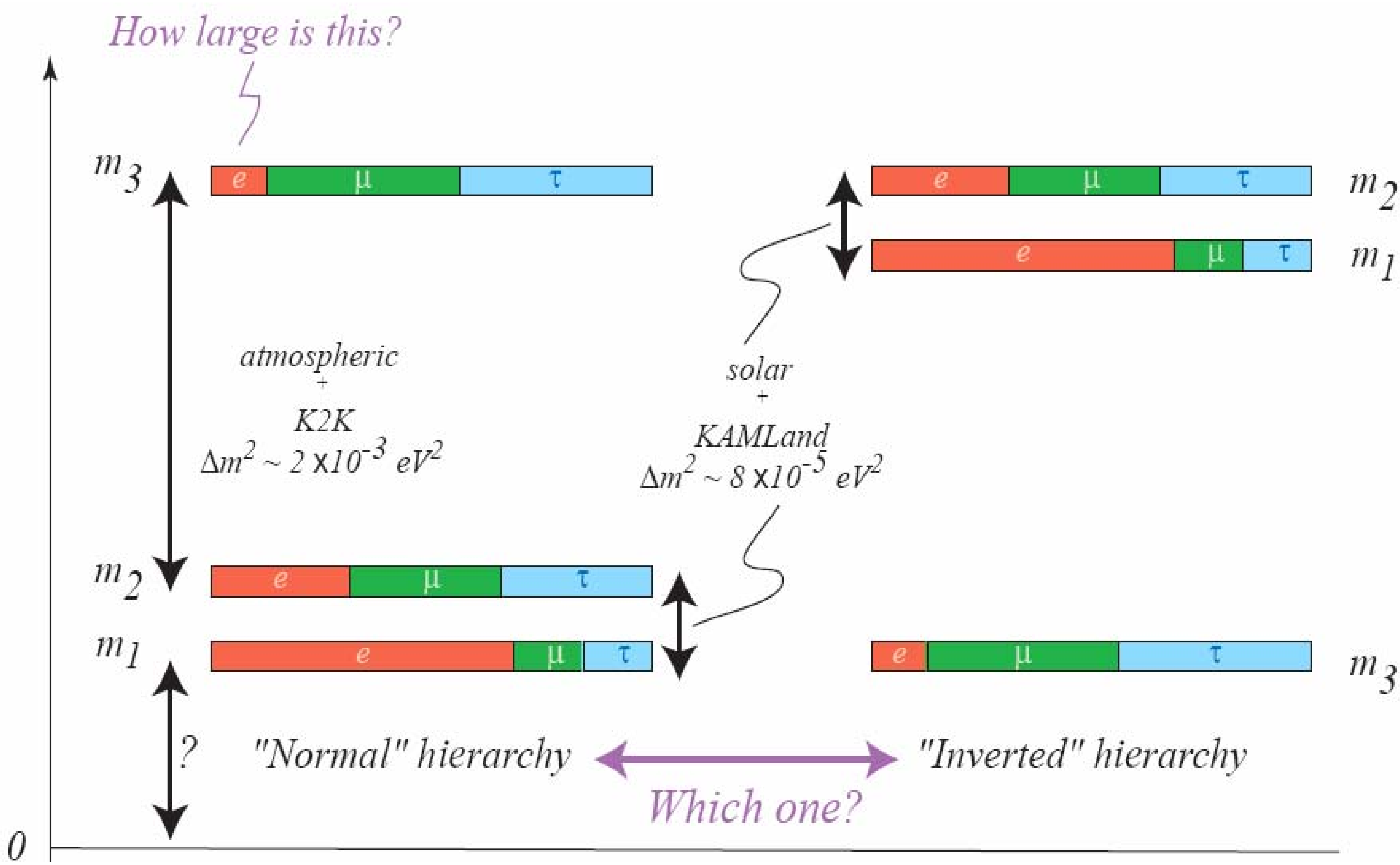
- Almost diagonal
- Third generation weakly coupled to first two
- "Wolfenstein Parameterization"

NEUTRINOS

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

- Mixing large
- No easy simplification
- Think of mass and weak eigenstates as totally separate

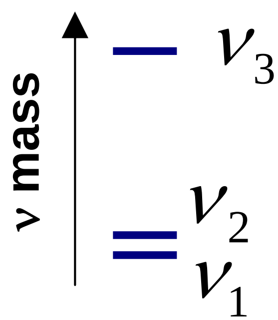
Neutrino Mixing (cont'd)



Incorporating LSND

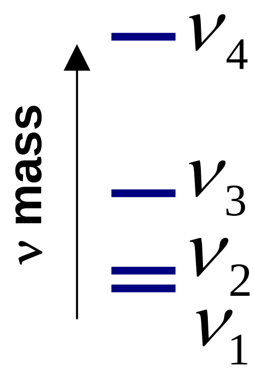
We have 3 very different Δm^2's. Very hard to fit with only three mass states…

Only 3 active ν:



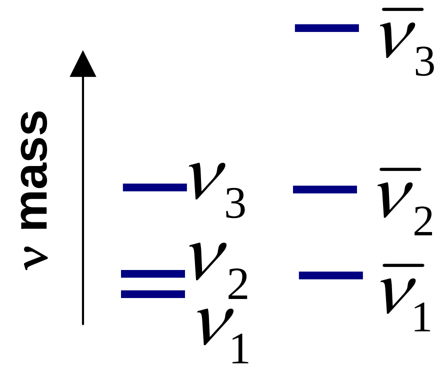
OR…

3 active+1 sterile ν:



OR…

CPT violation:



OR…

$$\begin{aligned}\text{solar}&:\nu_e \to \nu_\mu\\ \text{atmos}&:\nu_\mu \to \nu_e,\nu_\tau\\ \text{LSND}&:\bar{\nu}_\mu \to \bar{\nu}_\tau \to \bar{\nu}_e\end{aligned}$$

- not a good fit to data

$$\begin{aligned}\text{solar}&:\nu_e \to \nu_\mu,\nu_\tau\\ \text{atmos}&:\nu_\mu \to \nu_\tau\\ \text{LSND}&:\bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e\end{aligned}$$

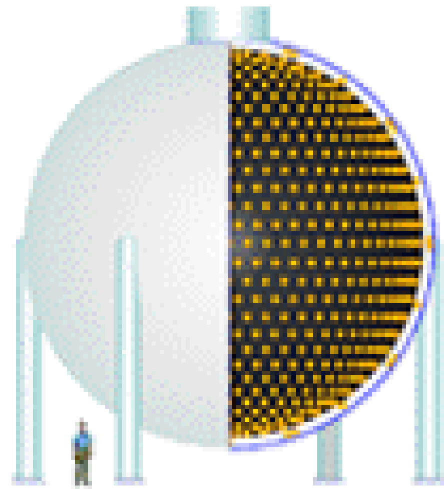
- possible(?)

$$\begin{aligned}\text{solar}&:\nu_e \to \nu_\mu\\ \text{atmos}&:\nu_\mu \to \nu_\tau\\ \text{LSND}&:\bar{\nu}_\mu \to \bar{\nu}_e\end{aligned}$$

- possible(?)

Can fit three mass states quite well *without* LSND, but no a priori reason to throw it out. Must check…

Enter the Fermilab Neutrino Program

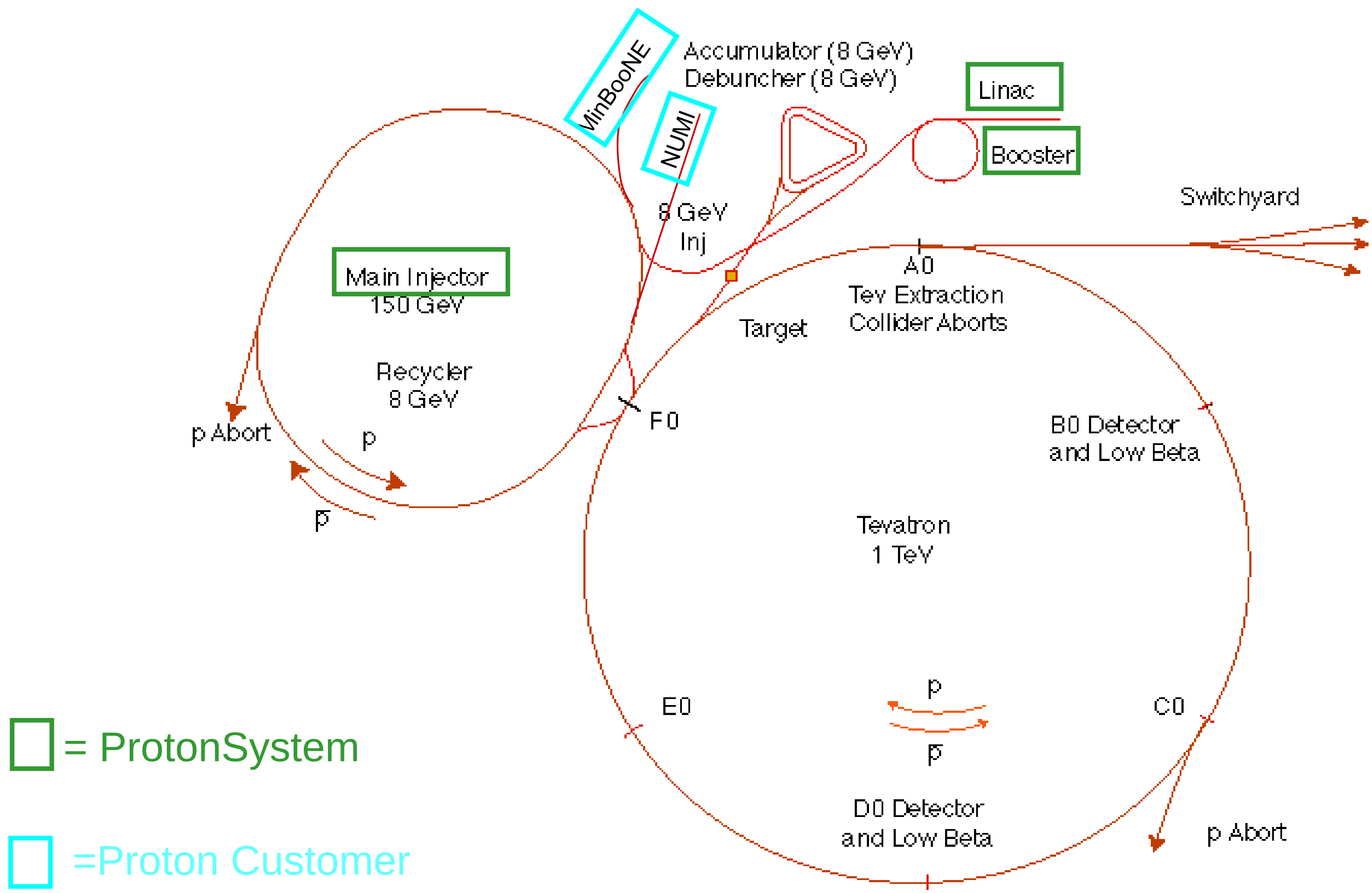


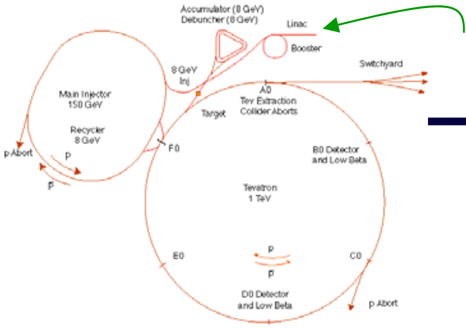
MiniBooNE-neutrinos from 8 GeV Booster proton beam (L/E~1): absolutely confirm or refute the LSND result

NuMI/Minos – neutrinos from 120 GeV Main Injector proton beam (L/E~100):

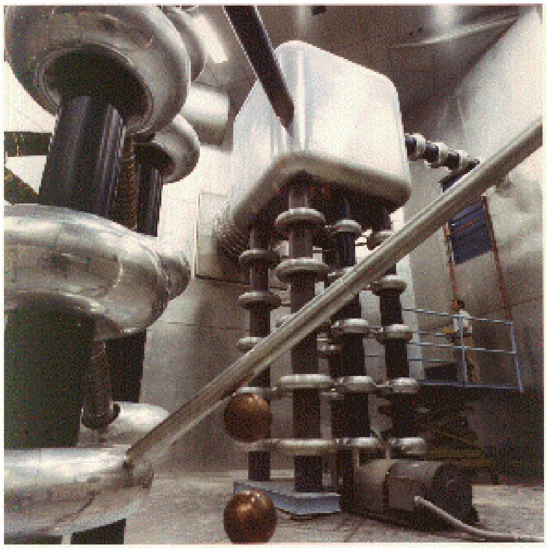
precision measurement of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations as seen in atmospheric neutrinos.

The Fermilab Accelerator Complex

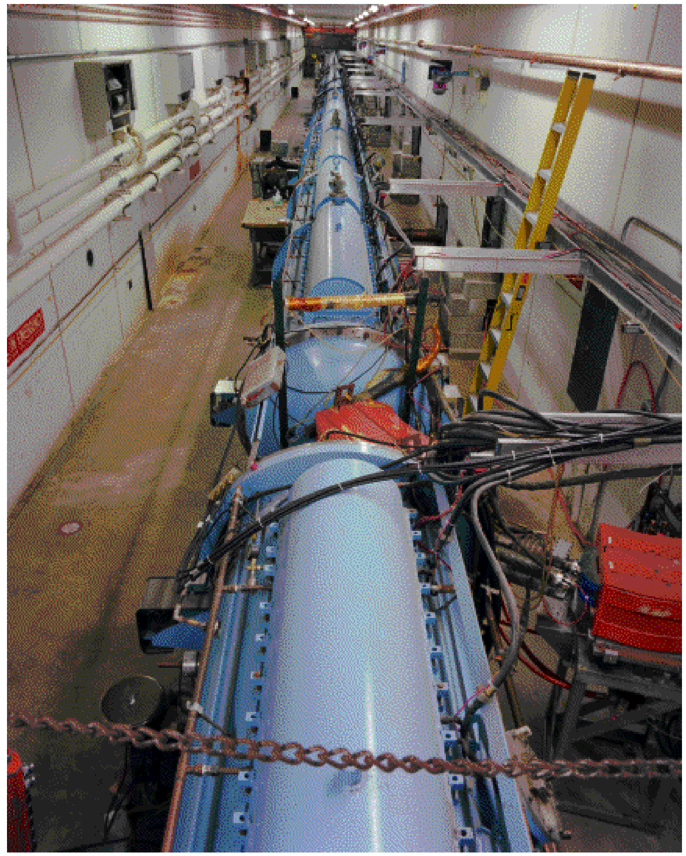




Preac(cellerator) and Linac

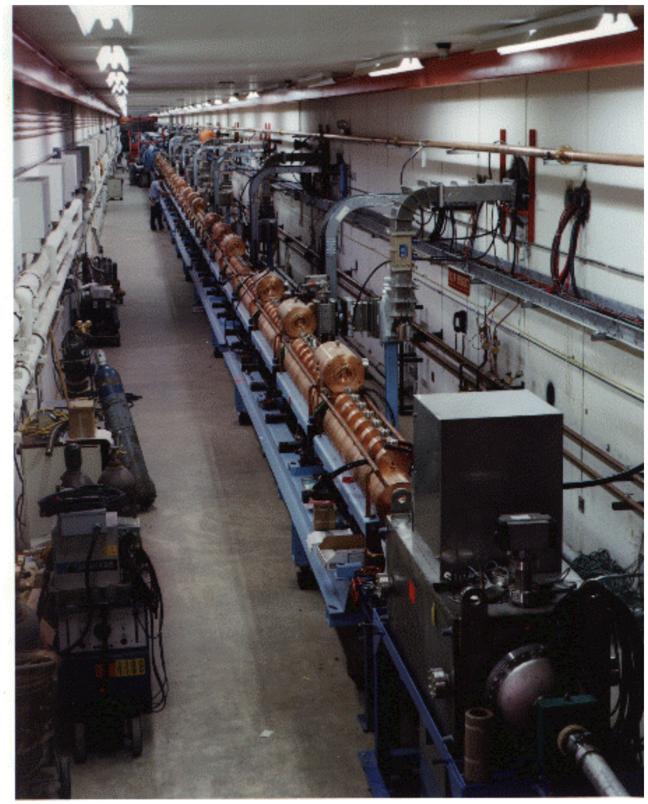


"Preac" - Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV.



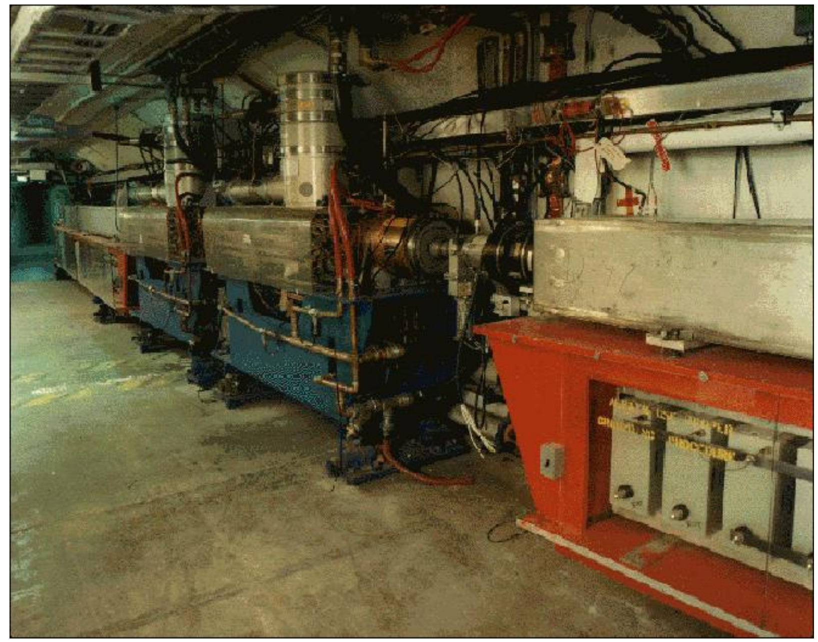
"Old linac"(LEL)- accelerate H- ions from 750 keV to 116 MeV

"New linac" (HEL)-
Accelerate H- ions from 116 MeV to 400 MeV

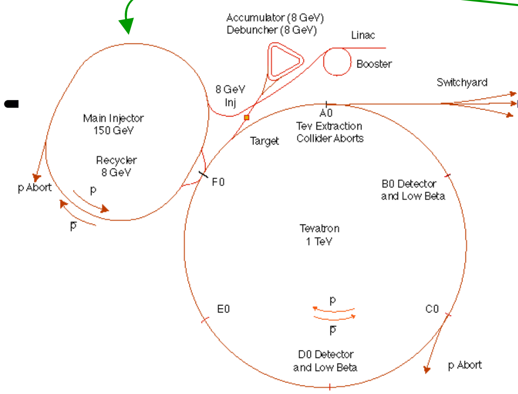


Booster

- Accelerates the 400 MeV beam from the Linac to 8 GeV
- From the Booster, beam can be directed to
  - The Main Injector
  - MiniBooNE (switch occurs in the MI-8 transfer line).
  - The Radiation Damage Facility (RDF) – actually, this is the old main ring transfer line.
  - A dump.
- More or less original equipment



Main Injector

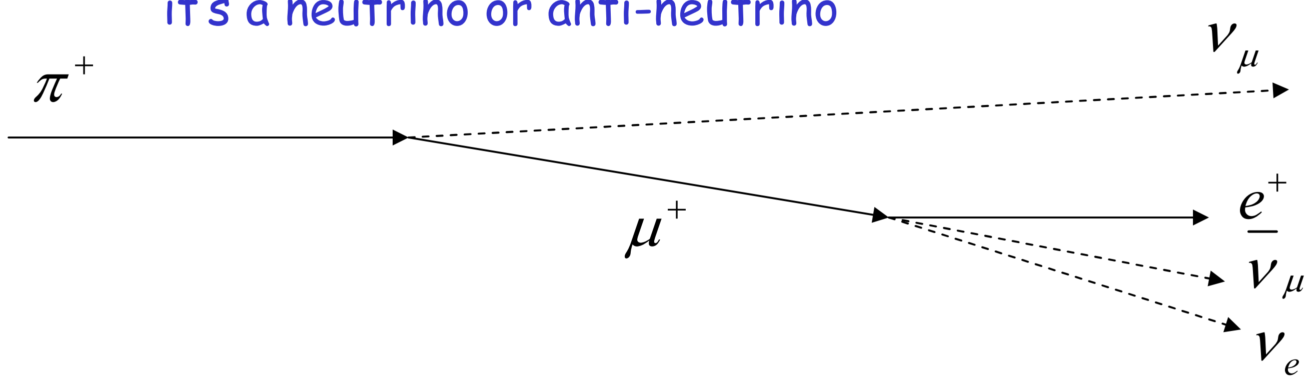


- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The Recycler (which shares the same tunnel)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.
  - The fixed target area.
  - The NUMI beamline.
- It can accelerate protons OR antiprotons to 150 GeV and inject them into the Tevatron.

Producing Neutrinos At an Accelerator

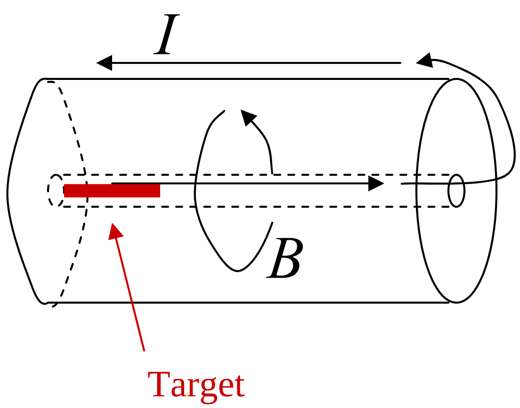
Pion sign determined whether it's a neutrino or anti-neutrino

We will look for these to oscillate



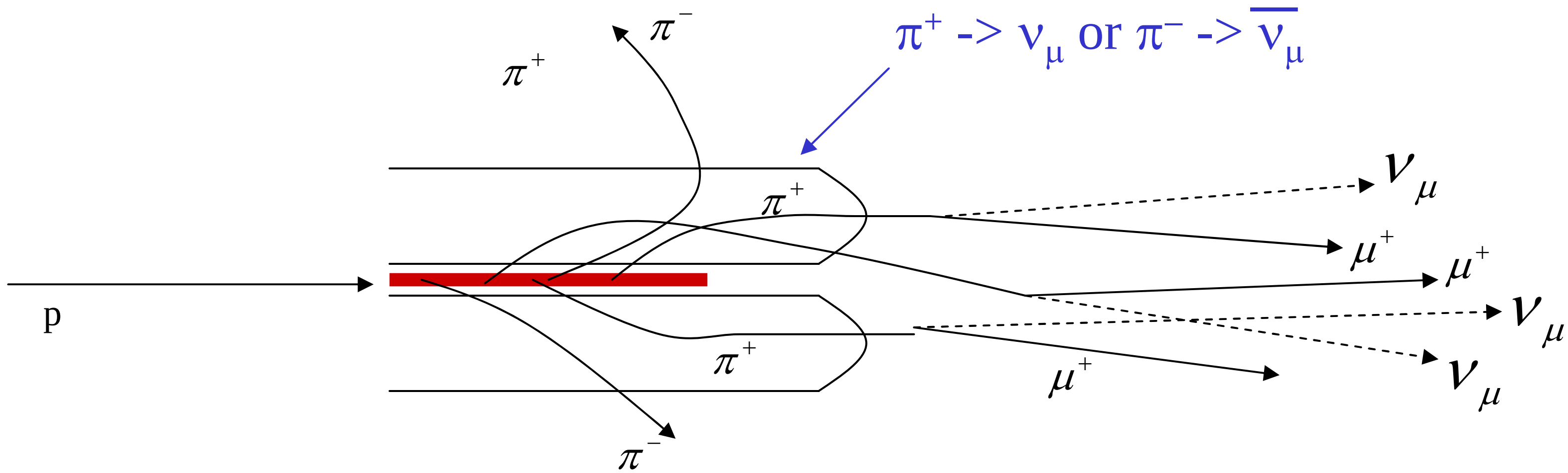
Neutrino Horn – "Focusing" Neutrinos

Can't focus neutrinos themselves, but they will go more or less where the parent particles go.



Coaxial "horn" will focus particles of a particular sign in both planes

Horn current selects
$\pi^+ \rightarrow \nu_\mu$ or $\pi^- \rightarrow \overline{\nu}_\mu$



So What's So Hard?

- Probability that a 150 GeV proton on the antiproton target will produce an accumulated pbar:

  .000015 (1.5E-5)

- Probability that a proton on the MiniBooNE target will result in a detected neutrino:

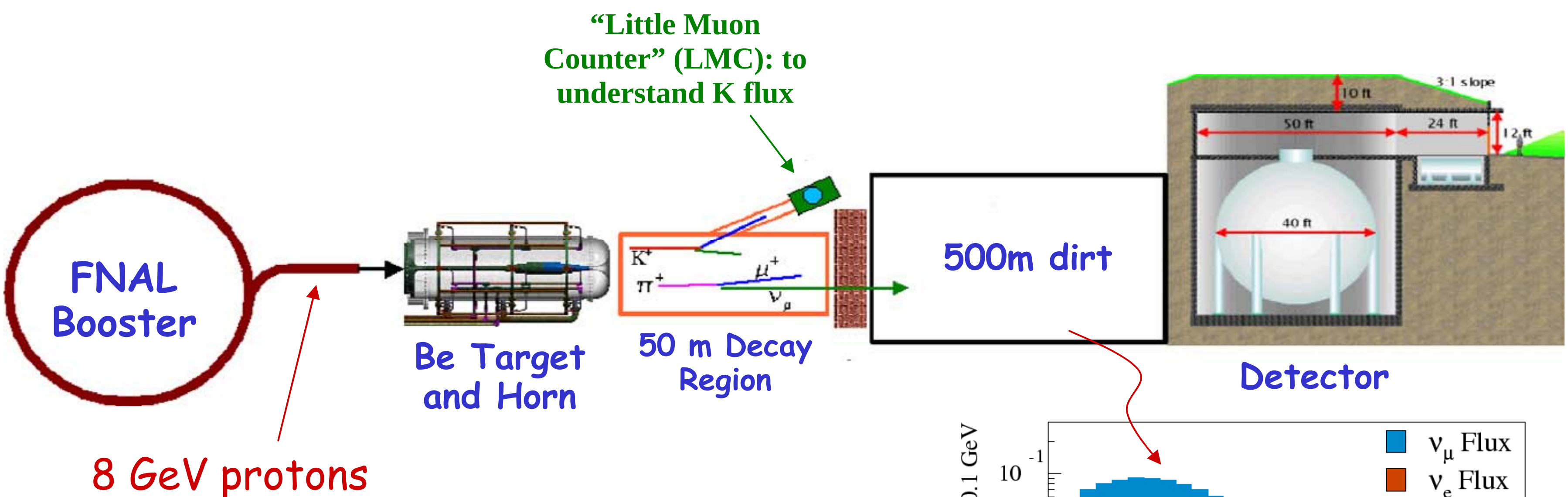
  .000000000000004 (4E-15)

- Probability that a proton on the NUMI target will result in a detected neutrino at the MINOS far detector:

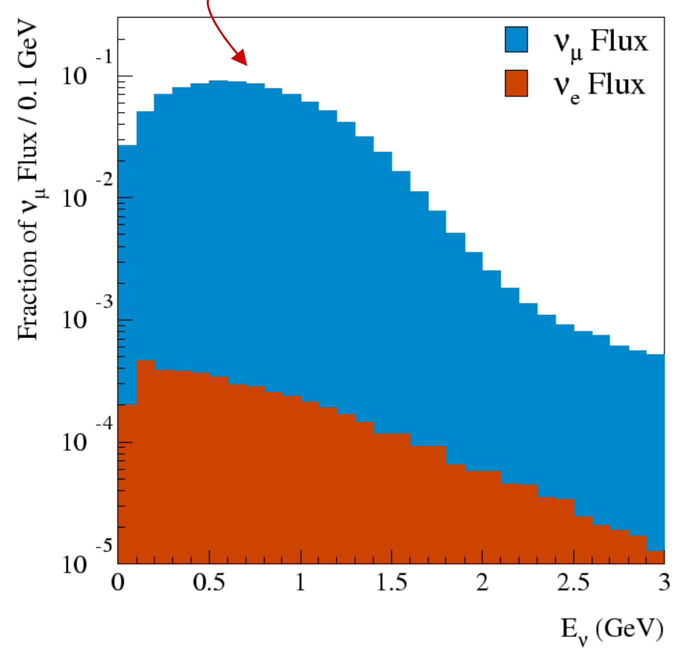
  .000000000000000025 (2.5E-17)

⇒ Need more protons in a year than Fermilab has produced in its lifetime!!

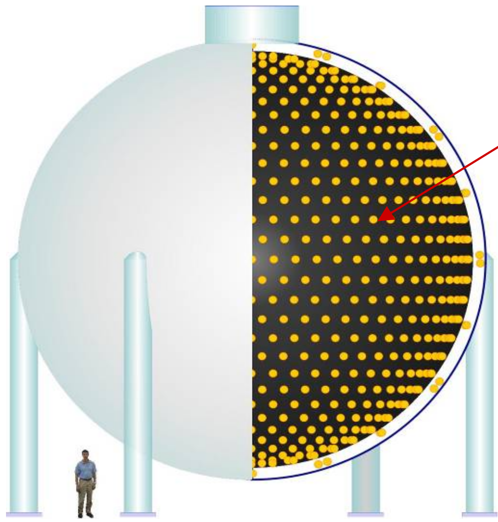
MiniBooNE Experiment



- Proton flux ~ 6E16 p/hr (goal 9E16 p/hr)
  - ~ 1 detected neutrino/minute
  - L/E ~ 1

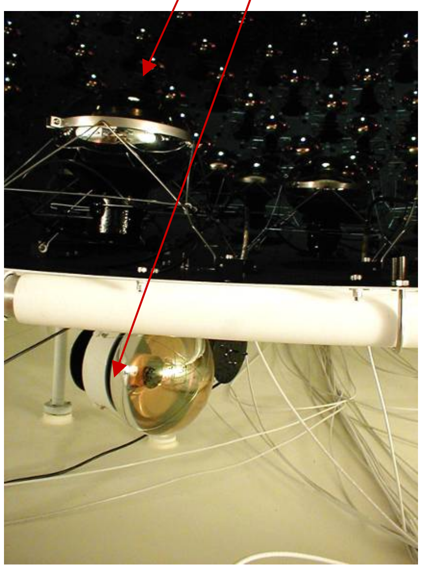


Detector



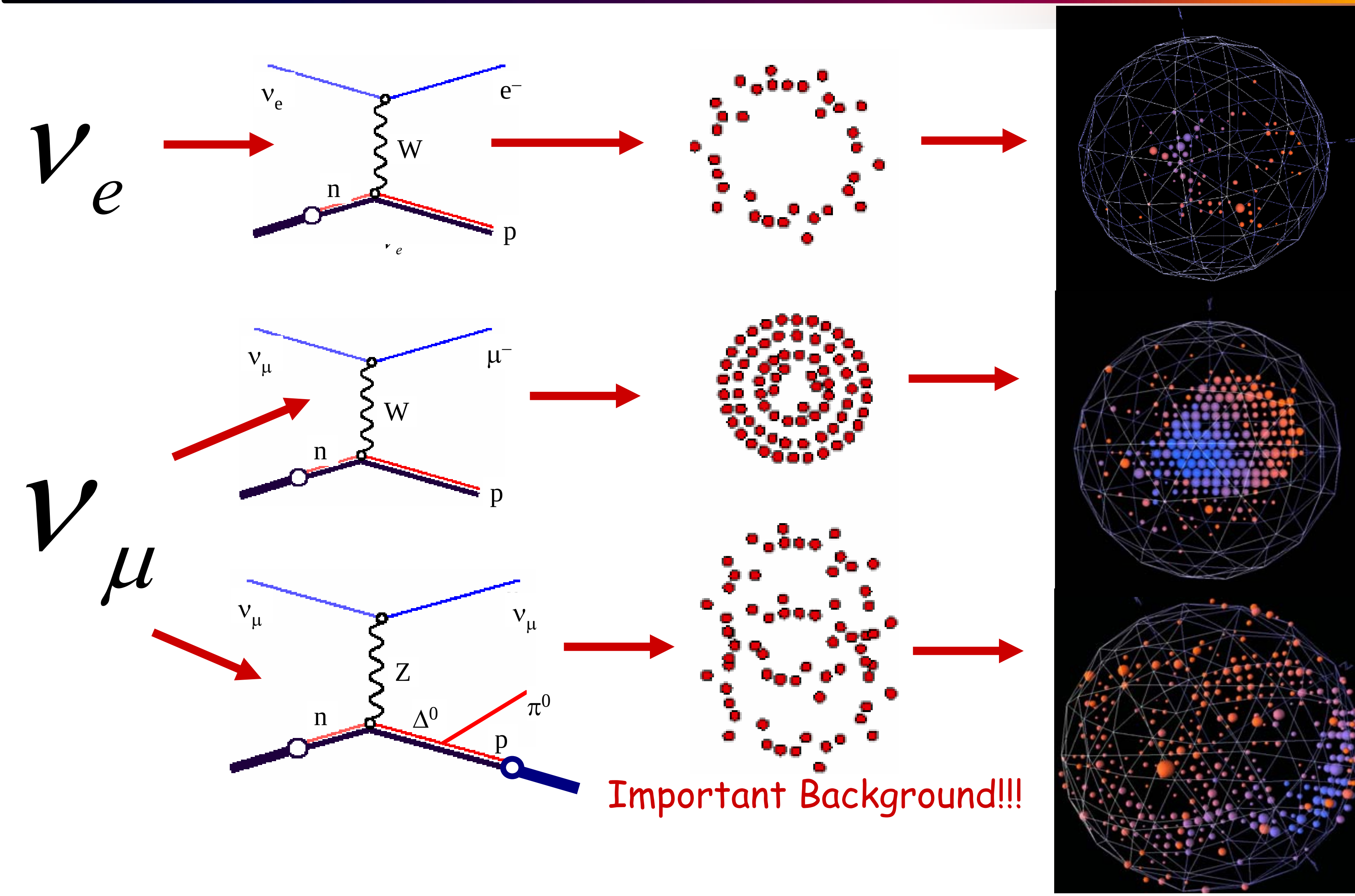
- 950,000 ℓ of pure mineral oil
- 1280 PMT's in inner region
- 240 PMT's outer veto region
- Light produced by Cerenkov radiation and scintillation

Light barrier

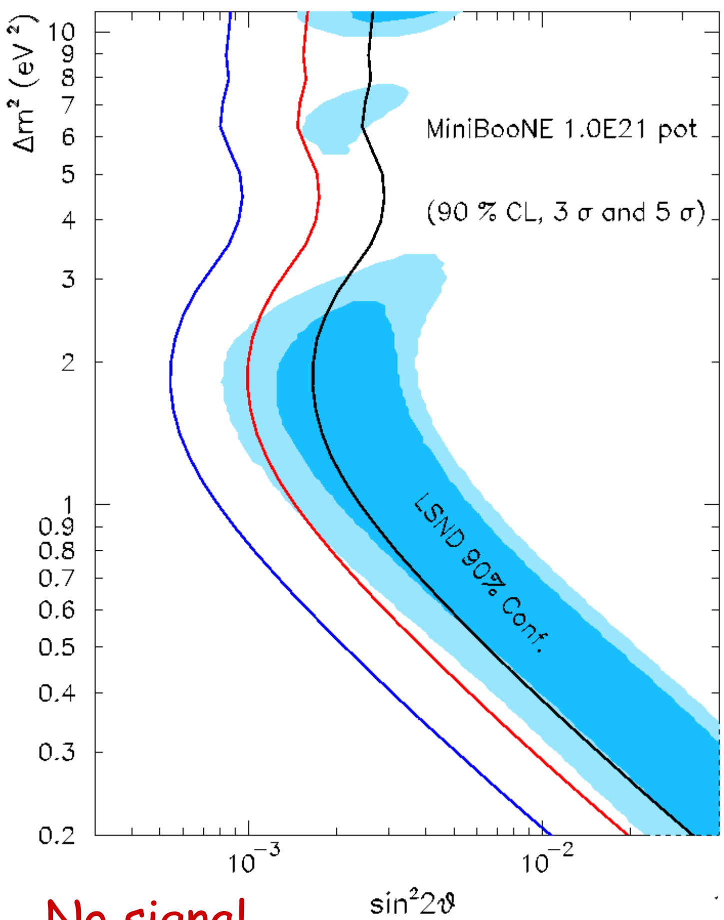


- Trigger:
  - All beam spills
  - Cosmic ray triggers
  - Laser/pulser triggers
  - Supernova trigger

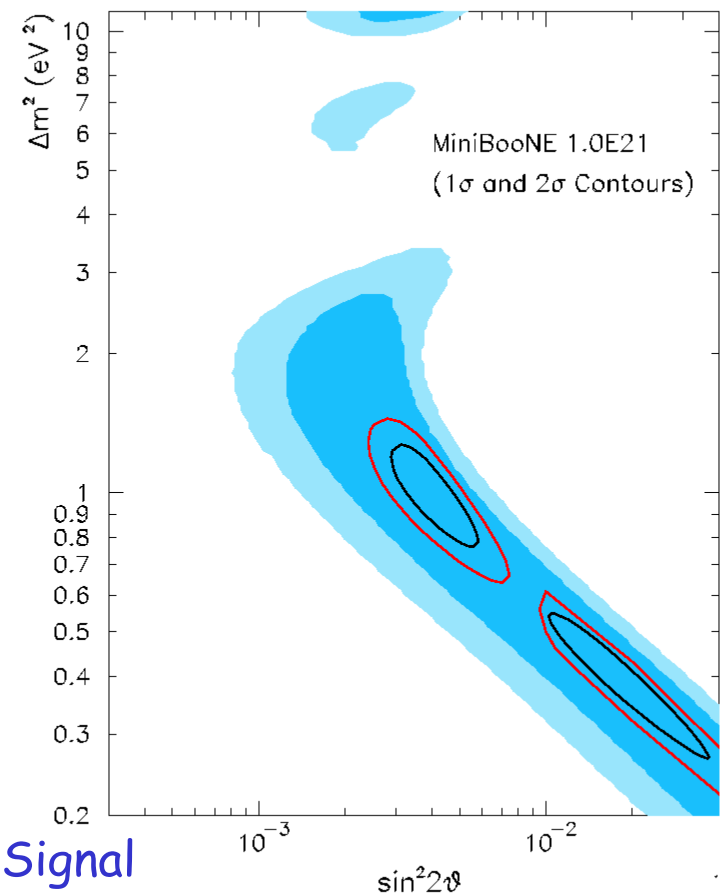
Neutrino Detection/Particle ID



Experimental Sensitivity (1E21 POT)

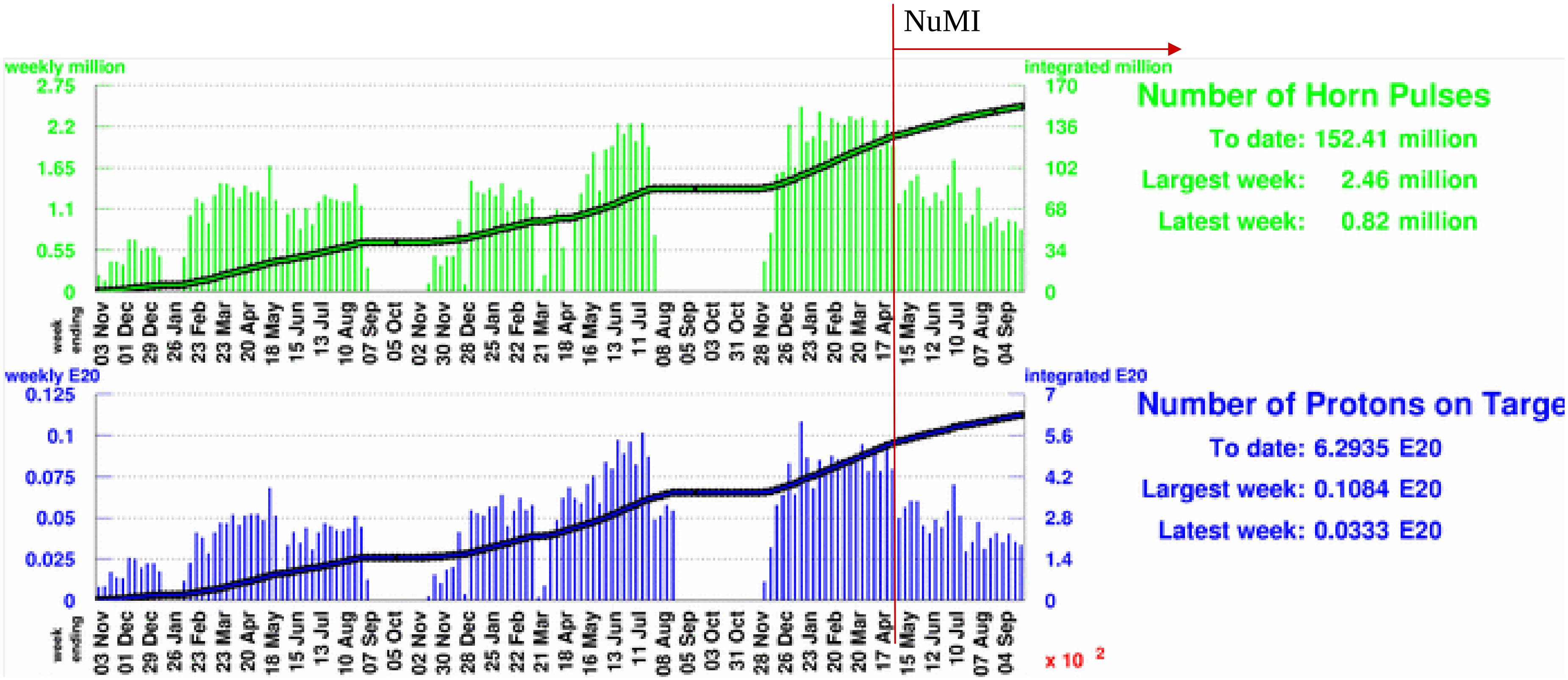


- No signal
  - Can exclude most of LSND at 5σ



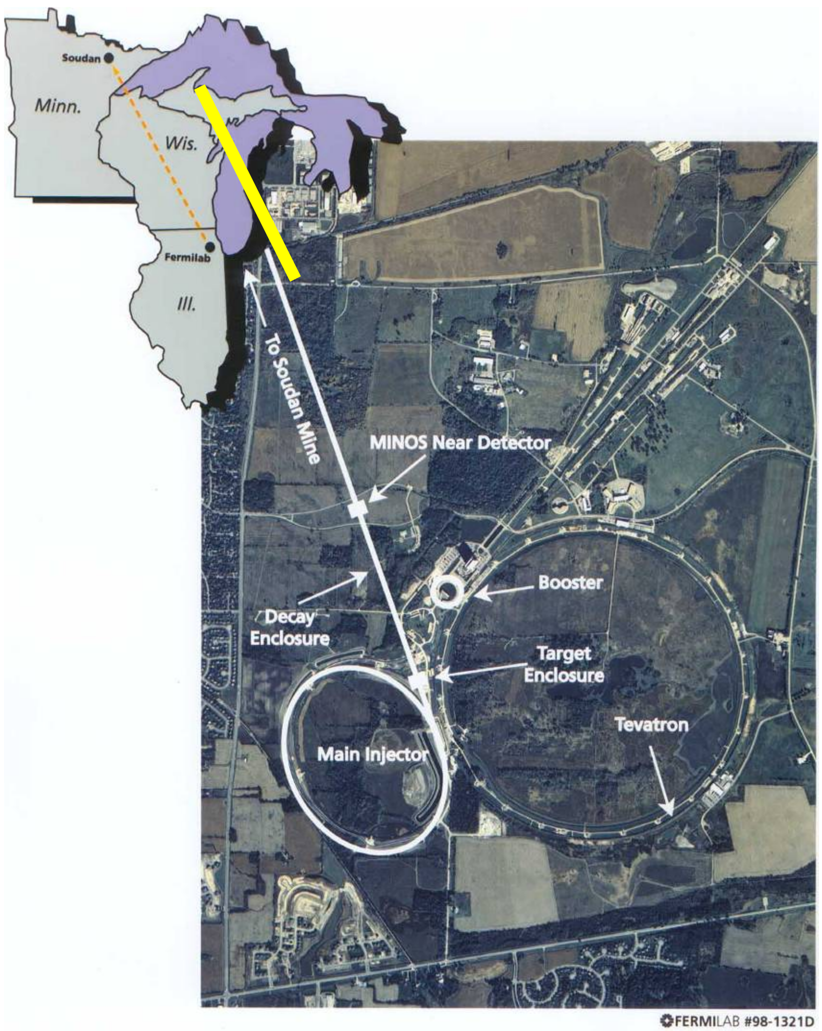
- Signal
  - Can achieve good Δm^2 separation

Beam to MiniBooNE



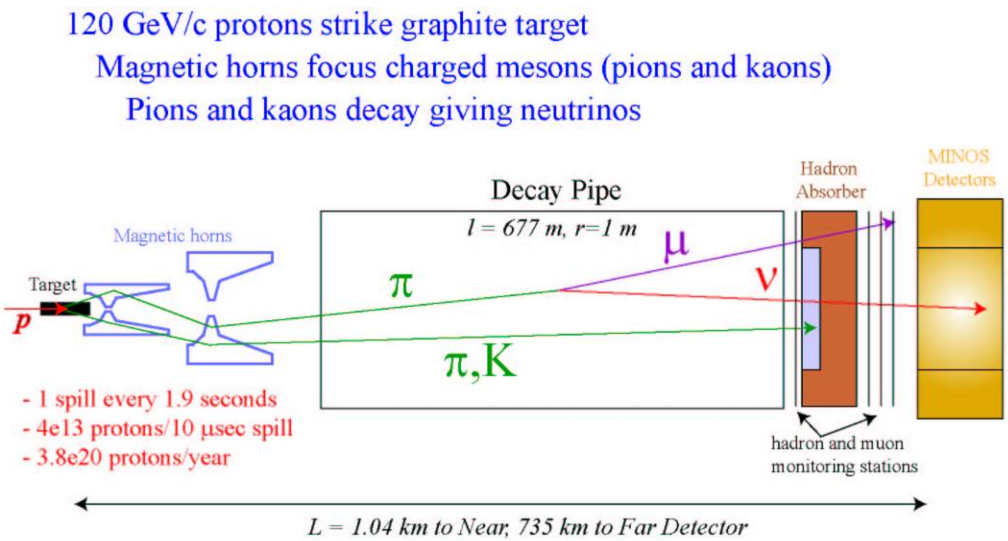
- 6.3E20 to date
- Plan for ~2E20/year during NuMI running
- First results in early 2006

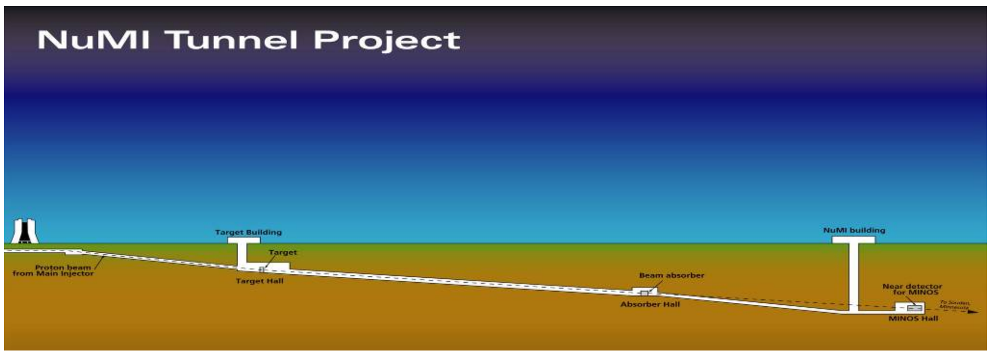
MINOS: Main Injector Neutrino Oscillation Study



- 8 GeV Booster beam is injected into Main Injector.
- Accelerated to 120 GeV
- Transported to target
- Two detectors for understanding systematic
  - Near detector: FNAL (L=1km)
  - Far detector: Sudan Mine in Minesota (735 km away)

NuMI beams



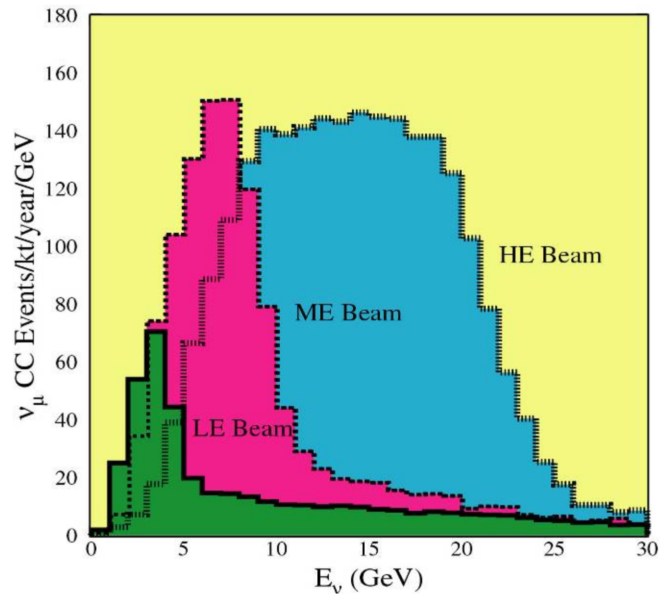


677 m decay pipe

Target

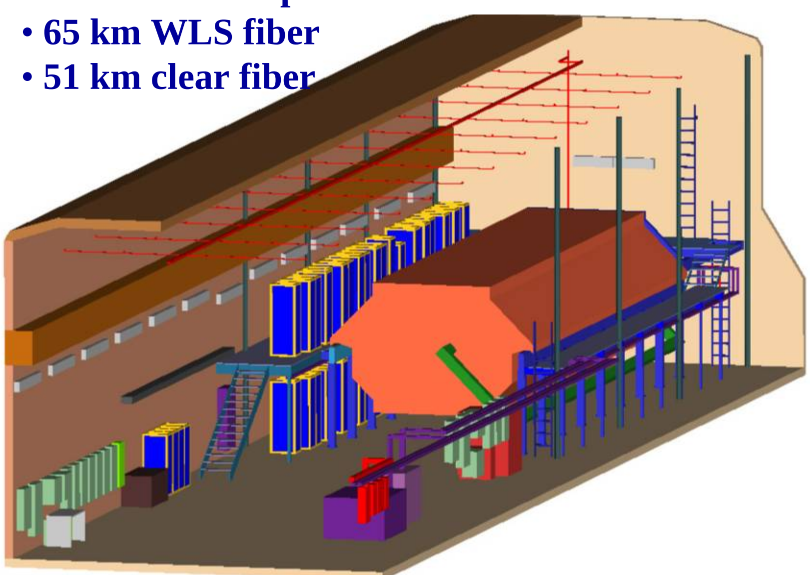
Near Detector

Two horns (second moveable) -> adjustable beam energy

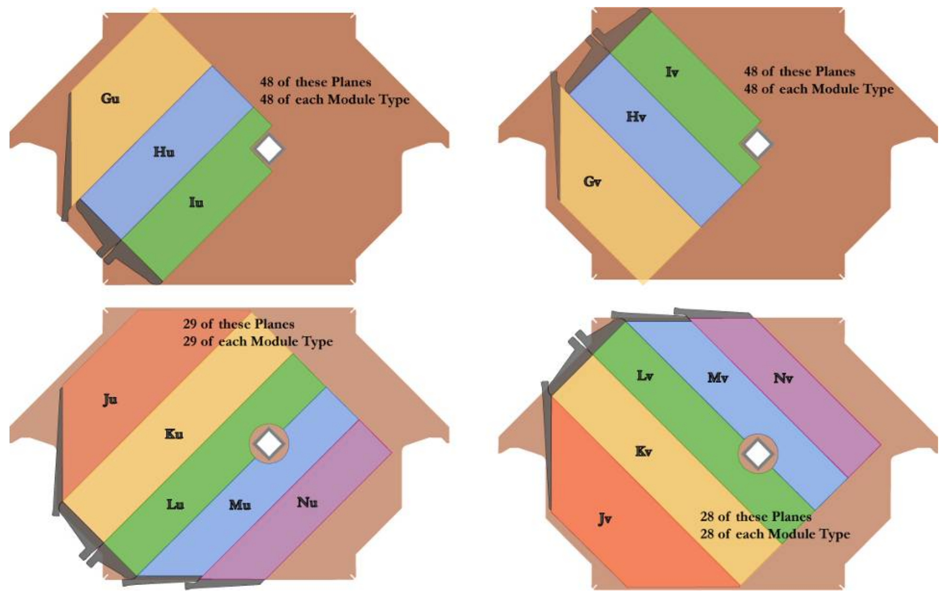


Near – 1040 m away

- veto - target - shower - μ spectrometer (detect neutrinos by μ appearance
- 1 kT
- 3.8 x 4.8 “squeezed” octagon
- 12,300 scint.strips
- 1-end readout
- no-multiplexing
- 220 M64s
- QIE-based front-end
- 282 steel planes
- 153 scintillator planes
- 65 km WLS fiber
- 51 km clear fiber



ν target region



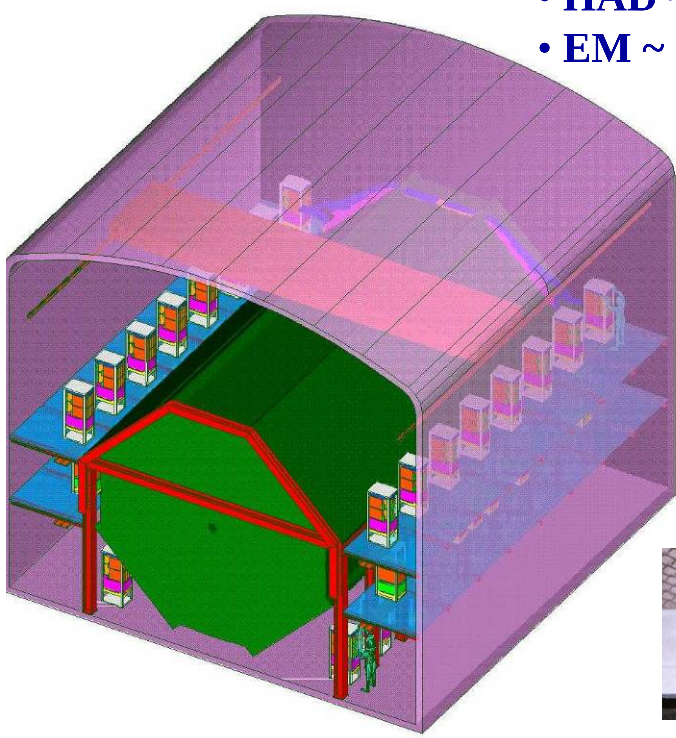
μ spectrometer region

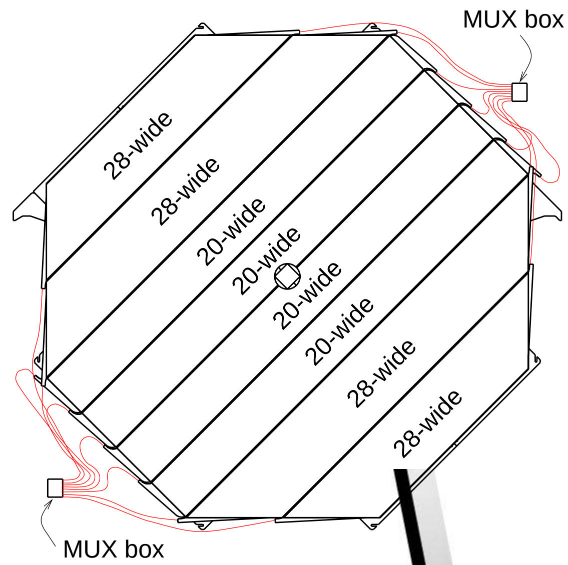
Near detector will provide high event statistics for “mundane” neutrino physics

Far Detector – 735.3 km away

- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- 92,928 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1452 M16s
- 722 km of WLS fiber
- 794 km of clear fiber

- B ~ 1.5T (R=2m)
- HAD ~ 55% / E $^{1/2}$
- EM ~ 23% / E $^{1/2}$

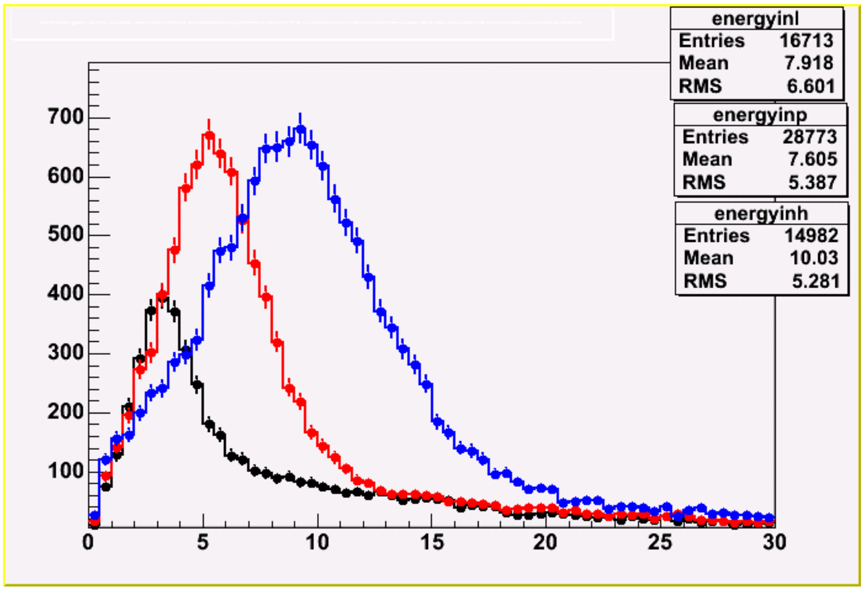




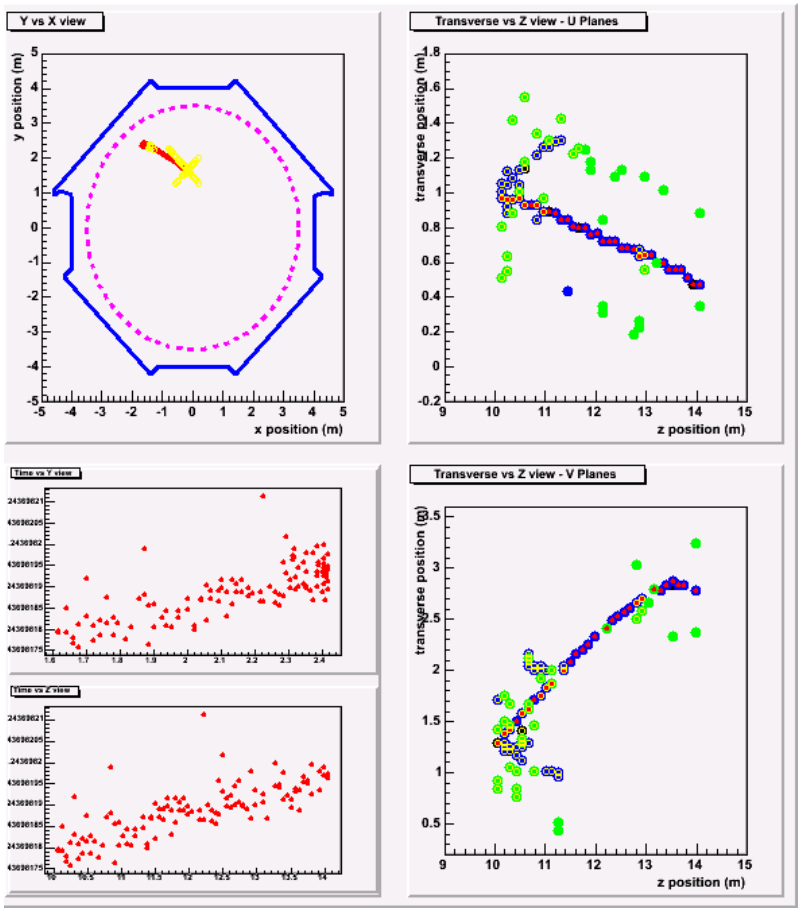
Minos Status

- Test Beam in December 2004
- Startup in March, 2005
- Collecting data steadily
- Detectors working well

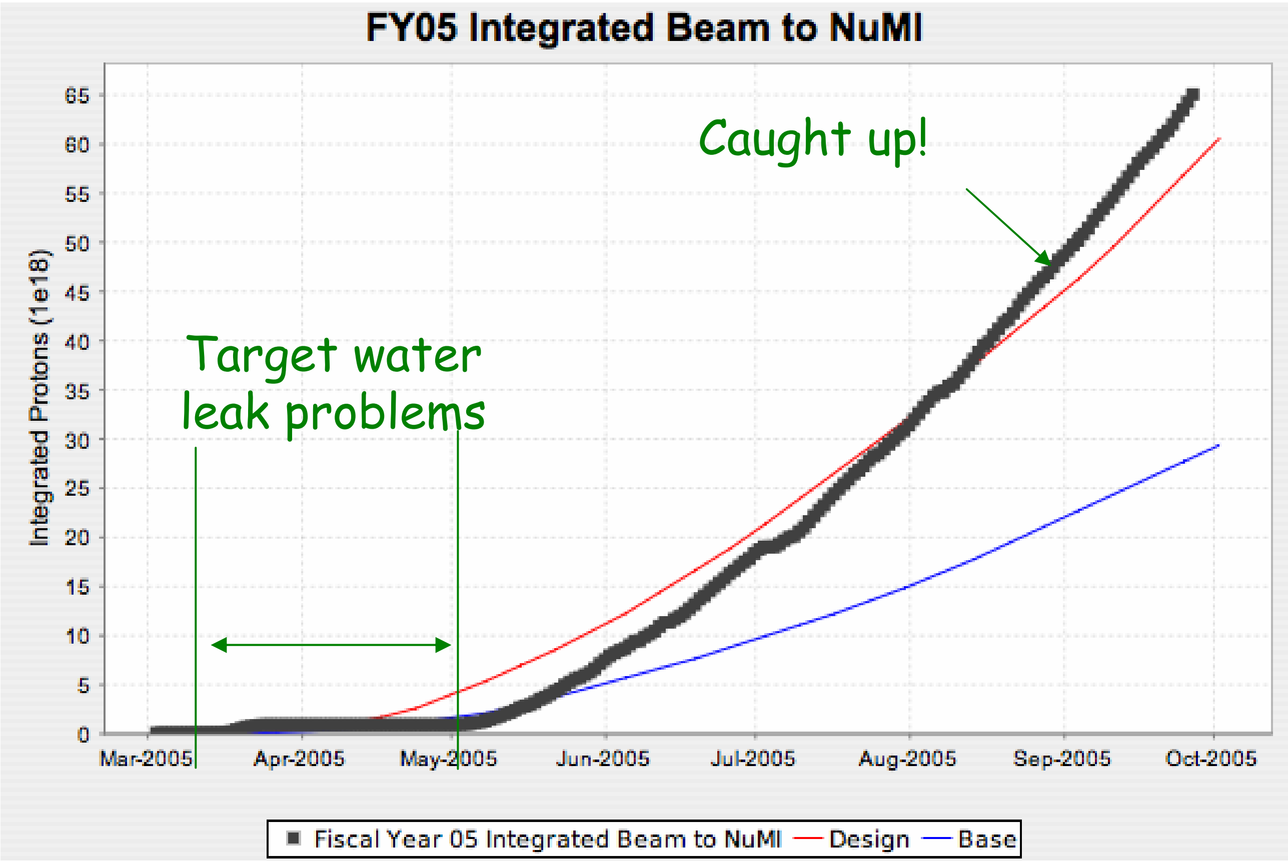
Near detector (different target positions)



Far detector (fully contained event)

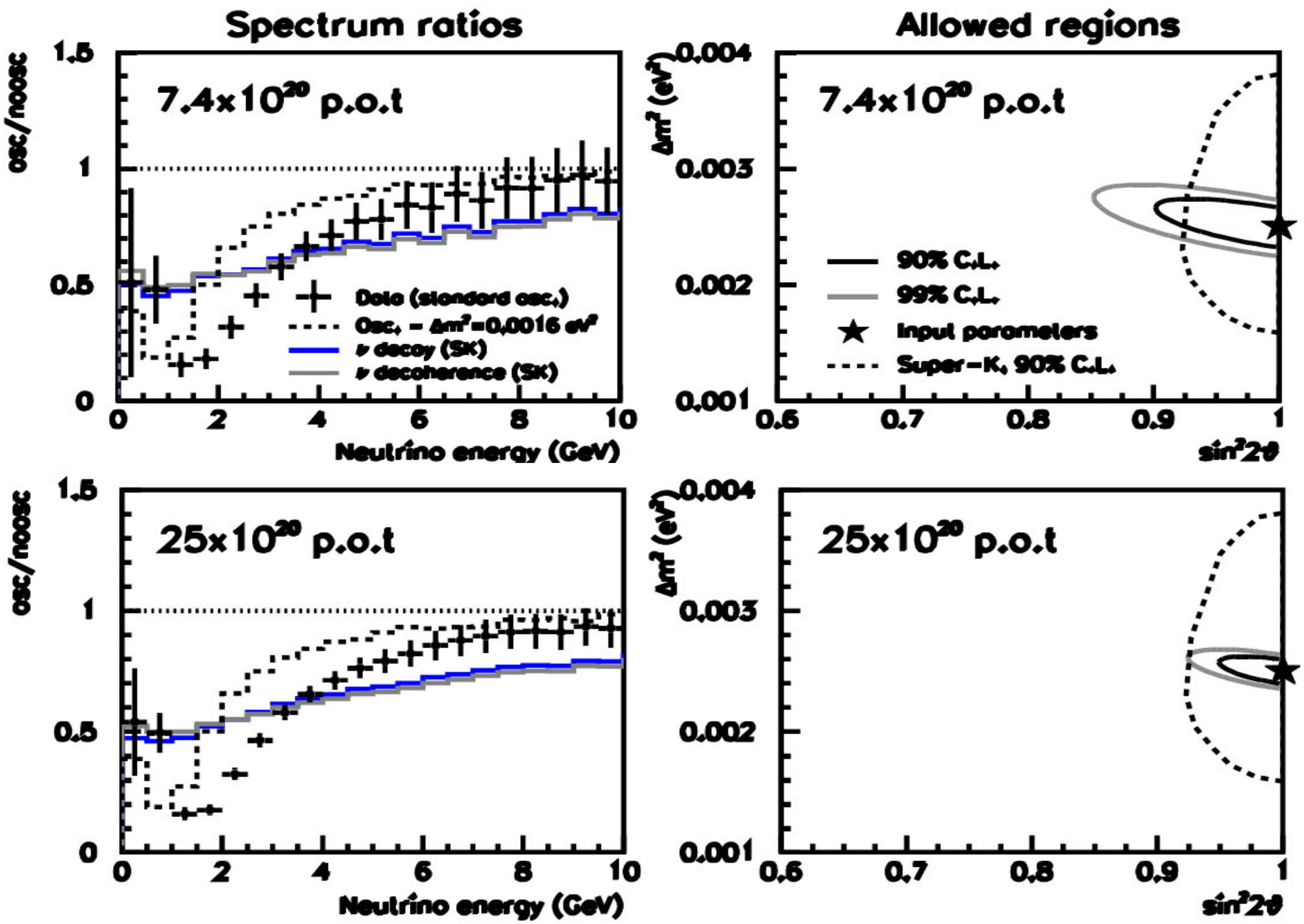


Beam to NuMI/MINOS



- Accumulating data at ~2-2.5E20/yr
- Can do initial oscillation result at 1E20 (~end of year)

MINOS Ultimate Sensitivity

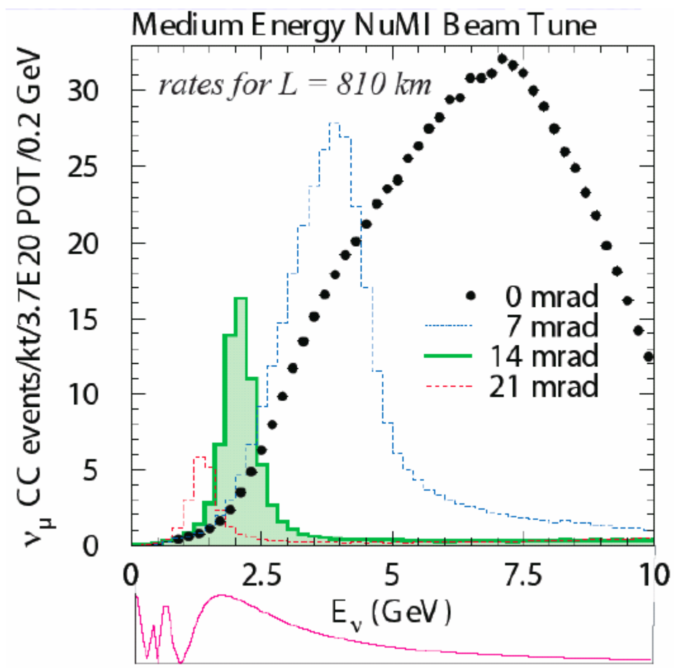


~3 years

~7 years

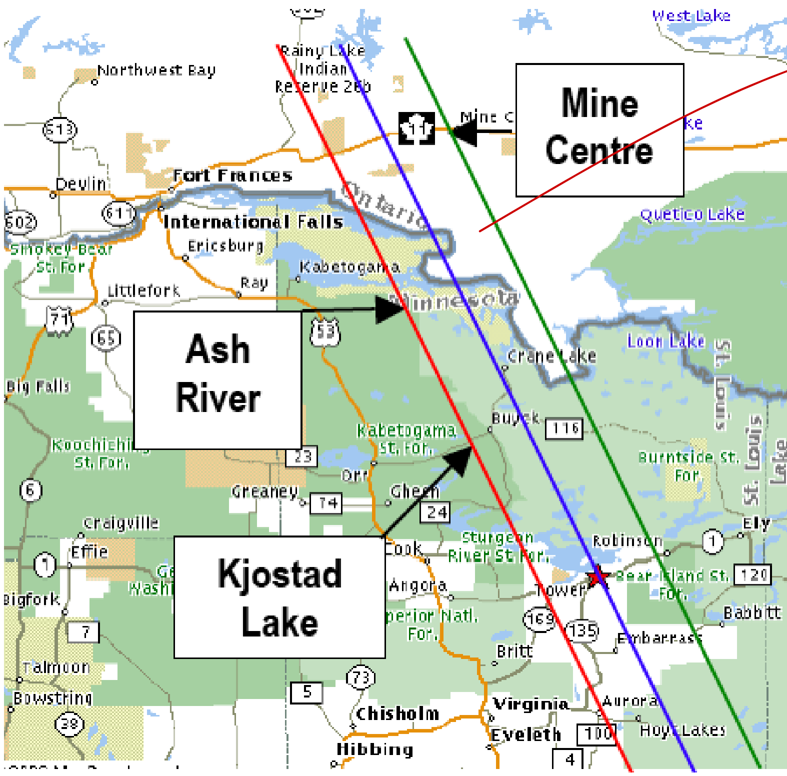
Beyond Minos – an Off-Axis experiment

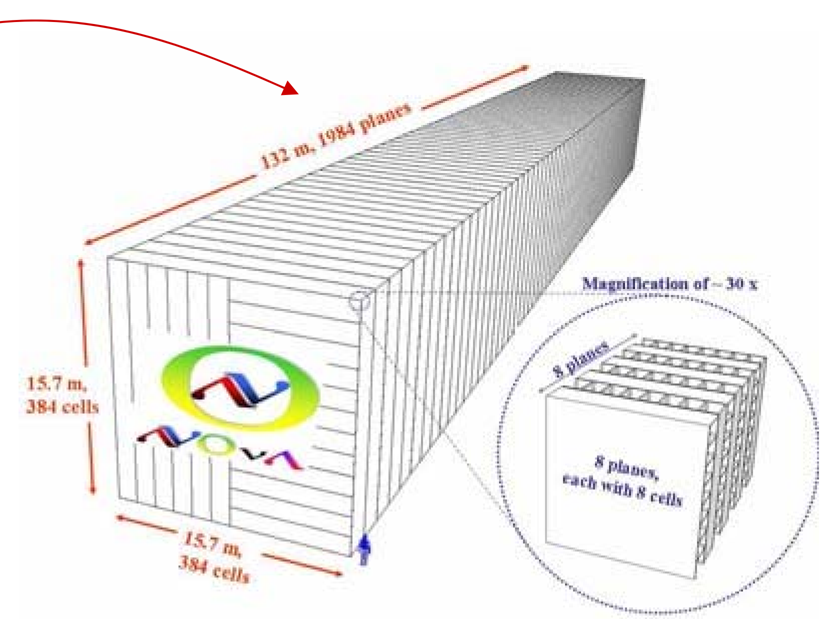
- Putting a Detector Off the NuMI Axis probes a narrower neutrino energy distribution than an on-axis experiment (albeit at a lower total intensity)
- By constraining L/E, one is able to resolve different contributions to the signal by comparing neutrino and anti-neutrino events
  - $\sin(\theta_{13})$
  - *Sign* of Δm^2 (resolve hierarchy question)
  - CP violation



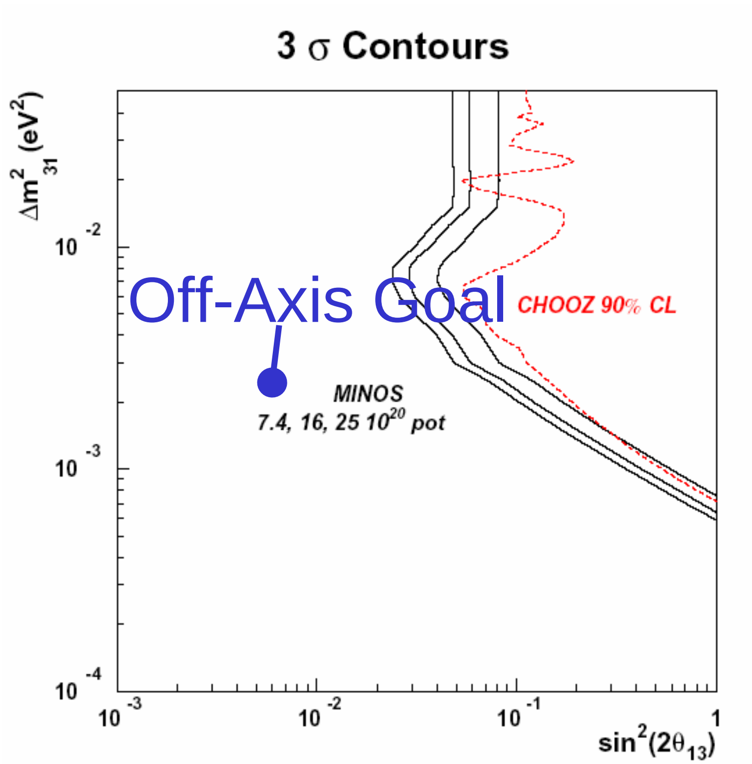
Nova Proposal

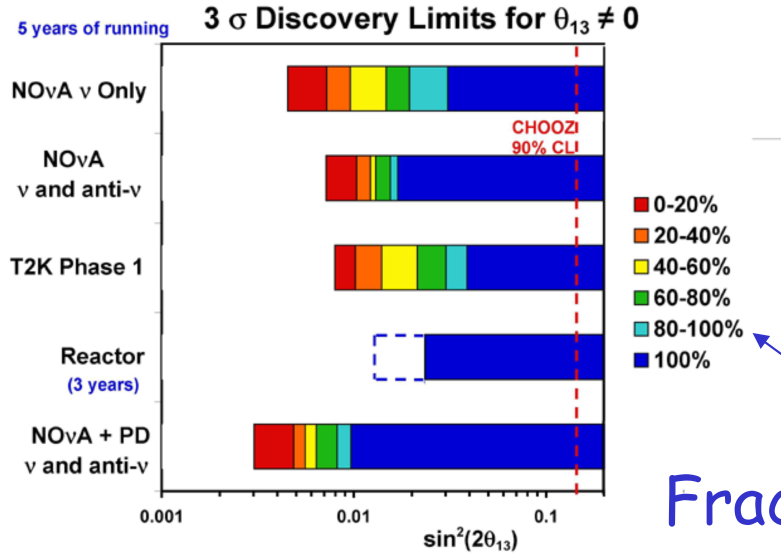
- Place a 30 kT fully active liquid scintillator detector about 14 mr off the NuMI beam axis

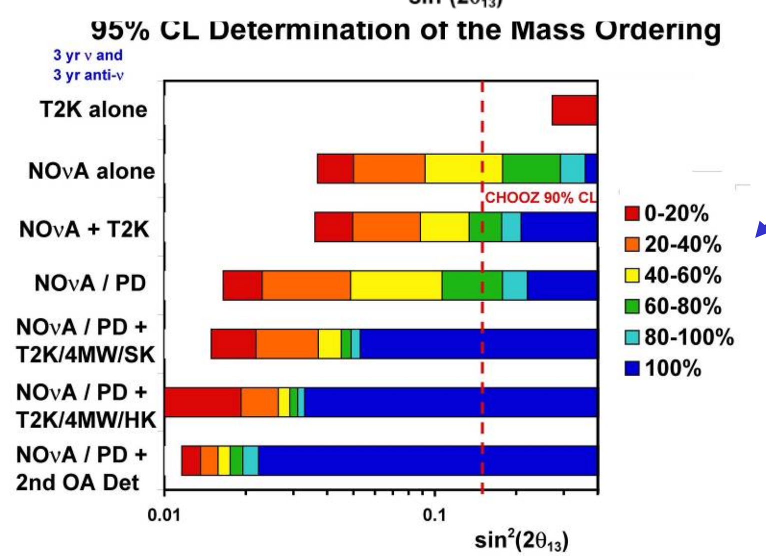




Nova Sensitivity





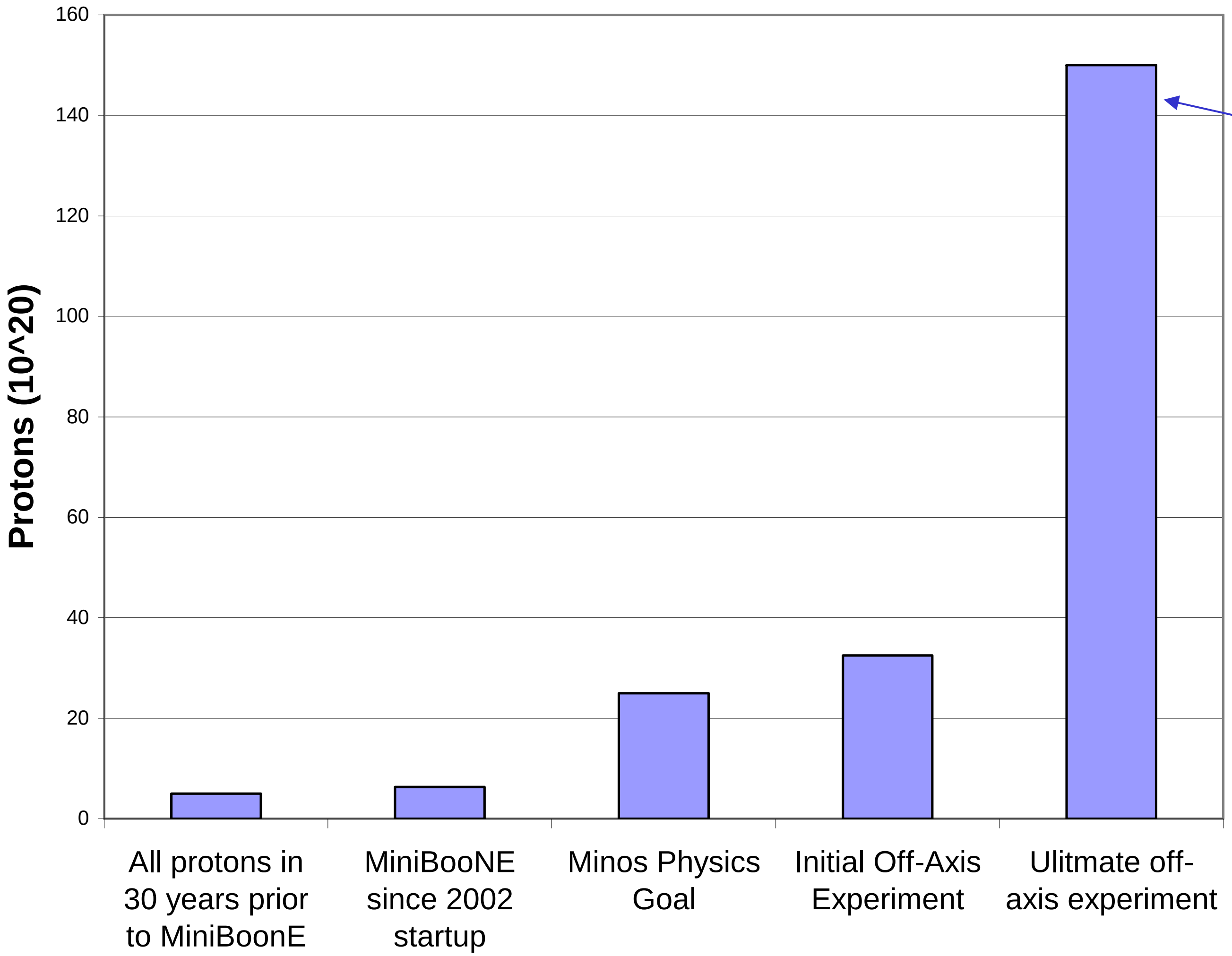


Fraction of δ covered

Nova Status and Schedule

- Stage I approval: April, 2005
- Project Start: October, 2006
- First kton operational: October, 2009
- All 30 ktons operations: July, 2011
- Problems:
  - Would really like a LOT of protons

Proton Demands (in Perspective)



Highest number I could find on a plot

Limits to Proton Intensity

- Total proton rate from Proton Source (Linac+Booster):
  - Booster batch size
    - Typical ~5E12 protons/batch
  - Booster repetition rate
    - 15 Hz instantaneous
    - Currently 7.5Hz average (limited by injection bump and RF cooling)
  - Beam loss
    - Damage and/or activation of Booster components
    - Above ground radiation

Operational Limit

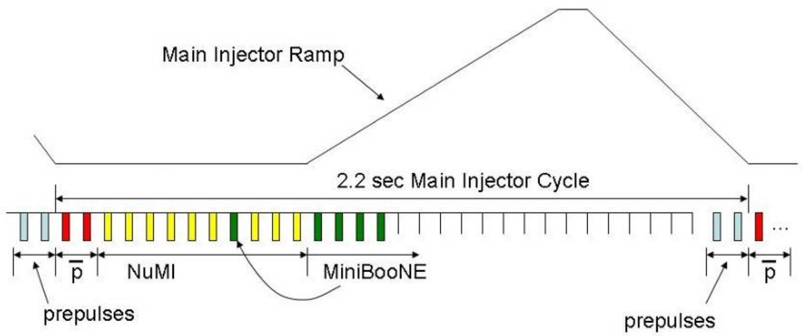
- Total protons accelerated in Main Injector:
  - Maximum main injector load
    - Six "slots" for booster batches (3E13)
    - Up to ~11 with slip stacking (5.5E13)
    - RF stability limitations (under study)
  - Cycle time:
    - 1.4s + loading time (1/15s per booster batch)

Staged Approach to Neutrino Program

- Stage 0 (now):
  - Goal: deliver 2.5E13 protons per 2 second MI cycle to NuMI (~2E20 p/yr)
  - Deliver 1-2E20 protons per year to Booster Neutrino Beam (currently MiniBooNE)
- Stage 1 (~2007):
  - A combination of Main Injector RF improvements and operational loading initiatives will increase the NuMI intensity to ~5E13 protons per 2.2 second cycle (~3.5E20 p/yr)
  - It is hoped we can continue to operate BNB at the 2E20 p/yr level during this period.
- Stage 2 (post-collider):
  - Proton to NuMI will immediately increase by 20%
  - Consider (for example) using the Recycler as a preloader to the Main Injector and reducing the Main Injector cycle time (~6.5E20 p/yr)
  - The exact scope and potential of these improvements are under study
- Stage 3 (proton driver)
  - Main Injector must accommodate 1.5E14 protons every 1.5 seconds
  - NuMI beamline and target must also be compatible with these intensities.

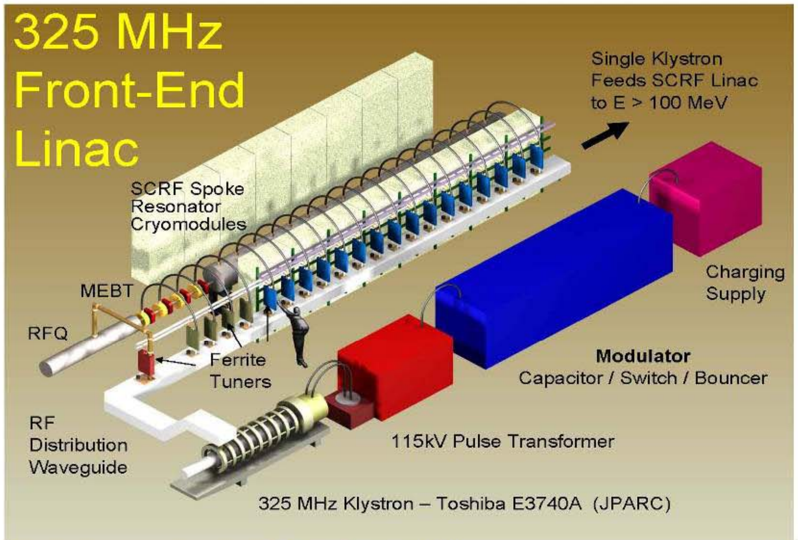
Re-tasking the Recycler

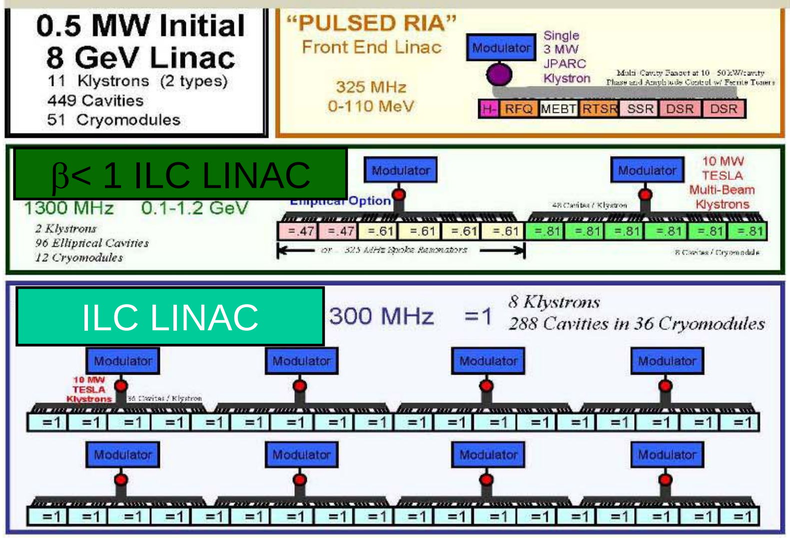
- At present, the Main Injector must remain at the injection energy while Booster "batches" are loaded.
  - Booster batches are loaded at 15 Hz
  - When we slip stack to load more batches, this will waste > 1/3 of the Main Injector duty factor.

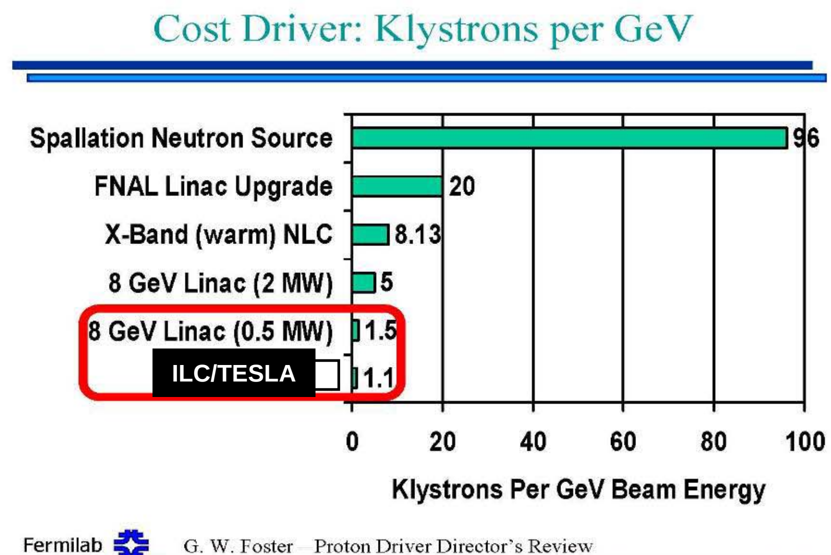


- After the collider, we have the option of "preloading" protons into the Recycler while the Main Injector is ramping, thereby eliminating dead time.
- Small invenstment
  - New beamline directly from Booster to Recycler
  - Some new RF
- Big payoff
  - At least 50% increase in protons to NuMI

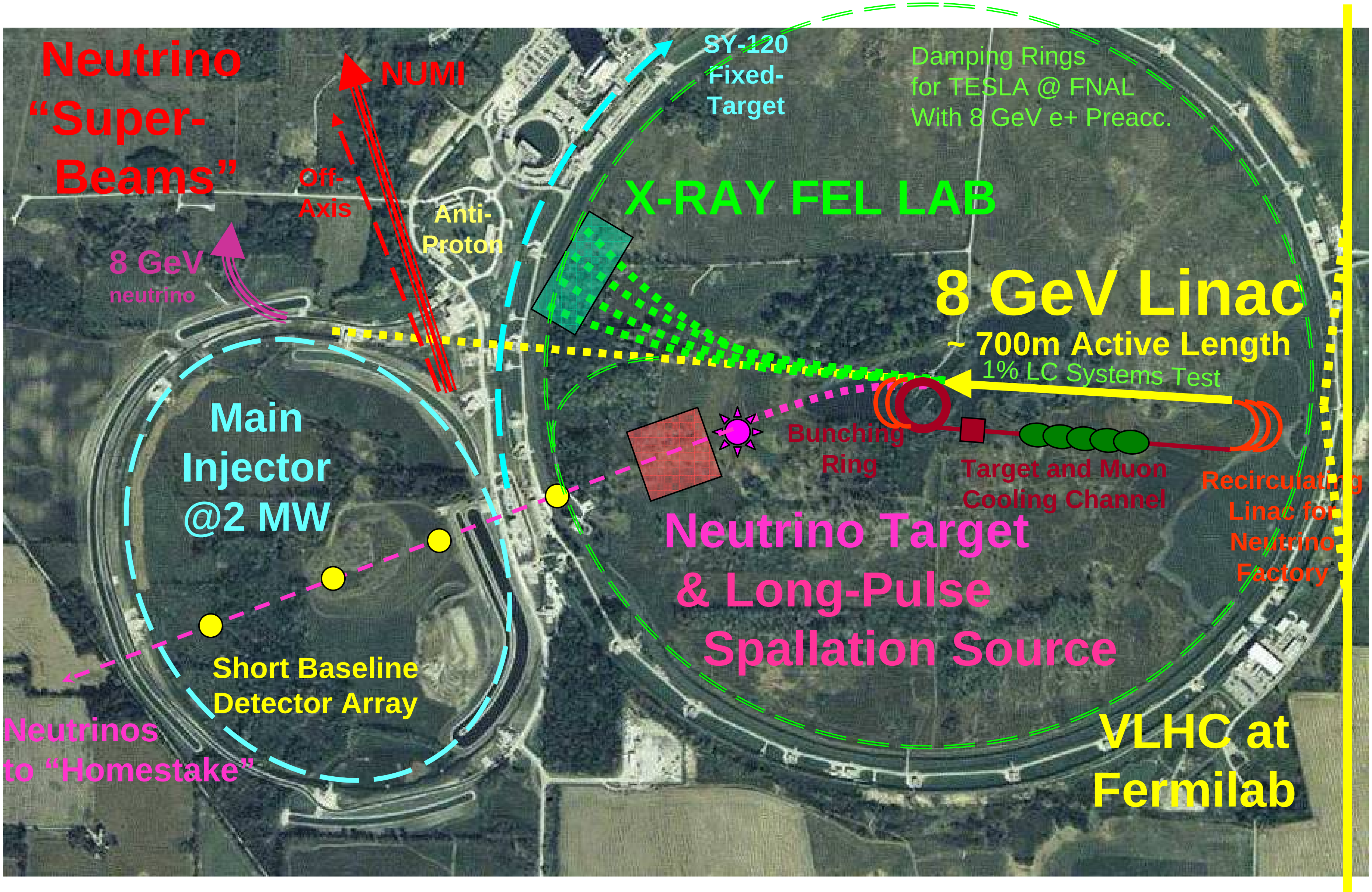
Thinking Big: A Proton Driver



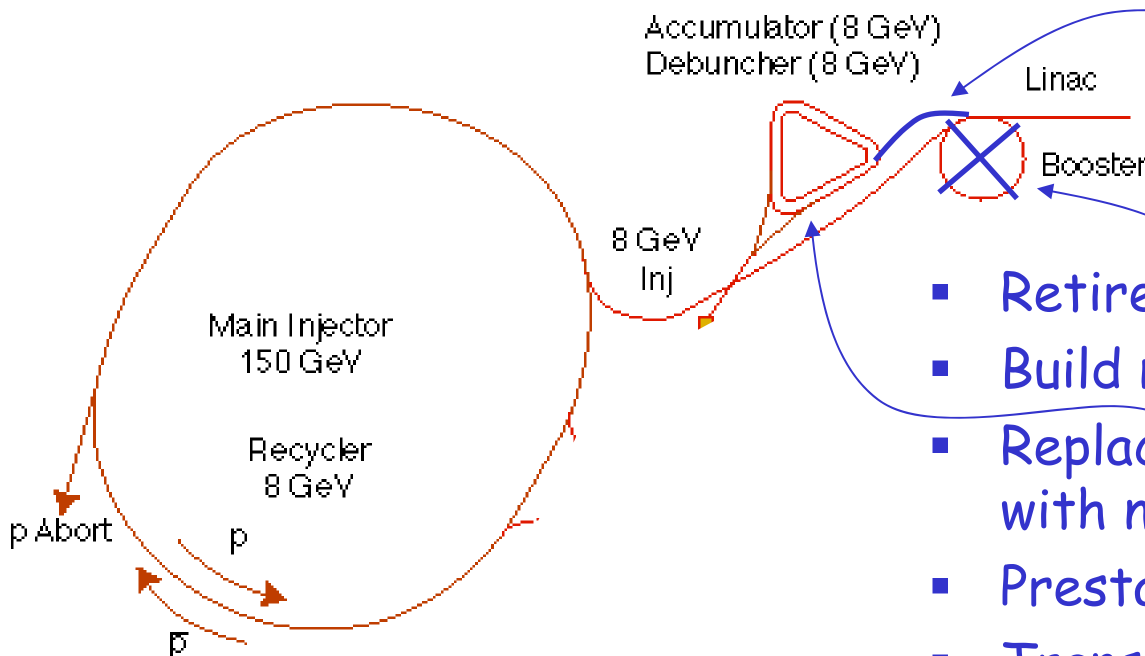




The Benefits of an 8 GeV Linac Proton Driver



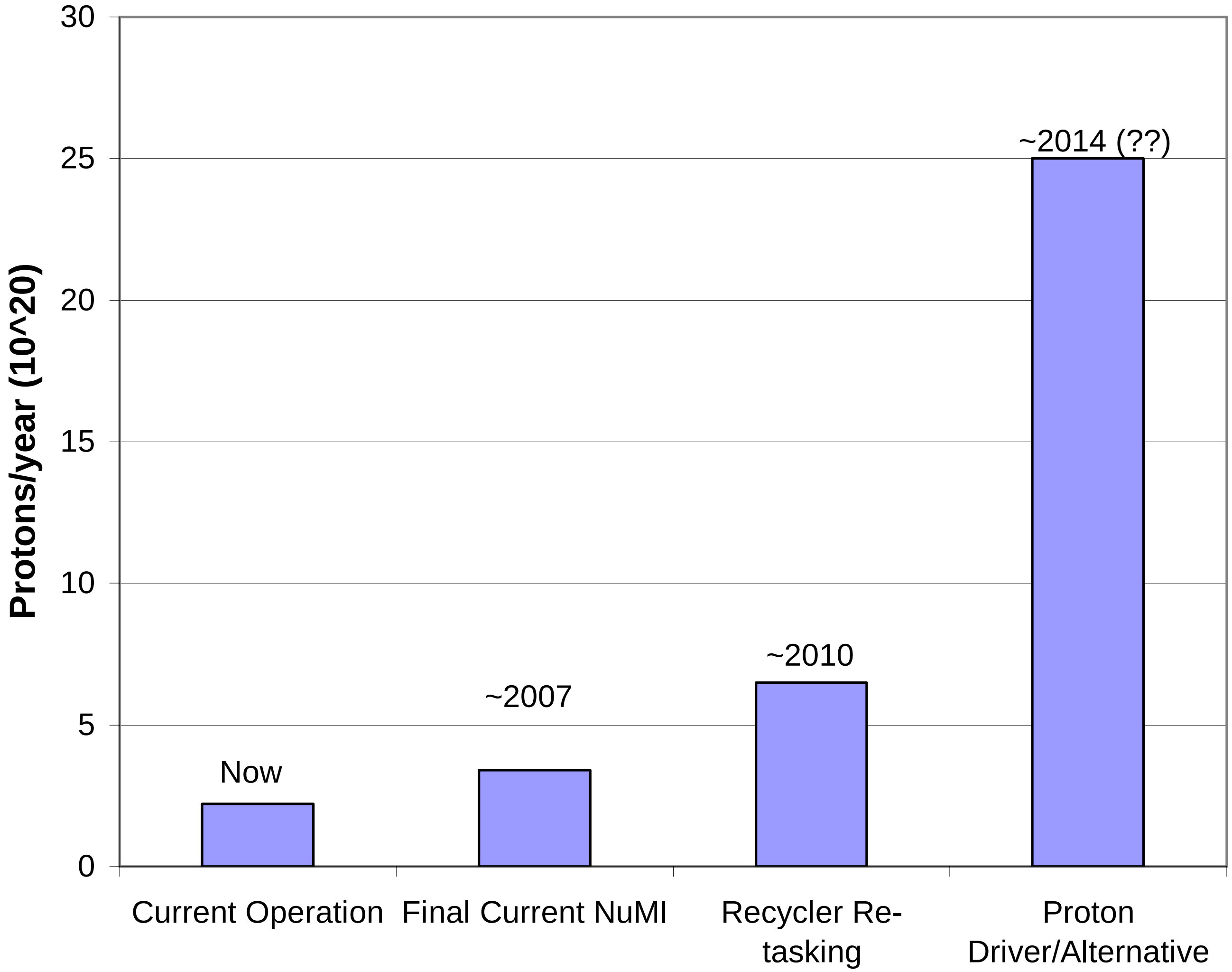
Possible "budget" Alternative to Proton Driver



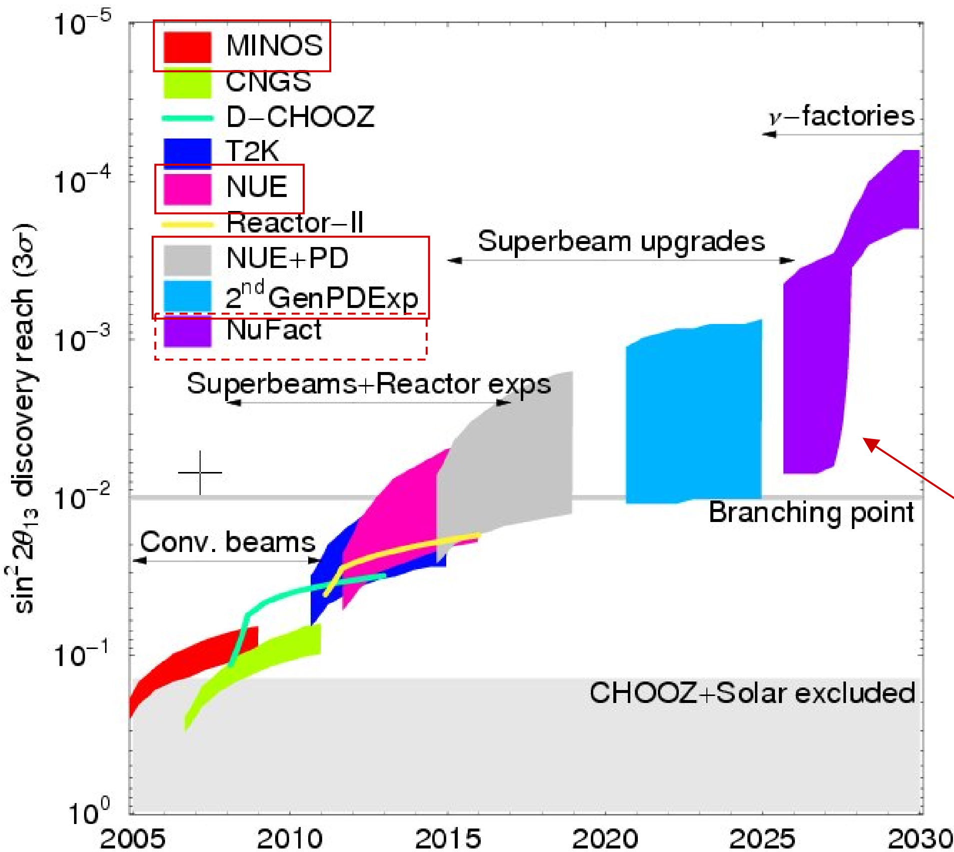
- Retire Booster
- Build new transfer line
- Replace pBar Debuncher with new Booster
- Prestack in Accumulator
- Transfer to recycler/Main Injector

- Less Expensive than the Linear Proton Driver
- Can get to 2 MW
- None of the side benefits
- No synergy with ILC

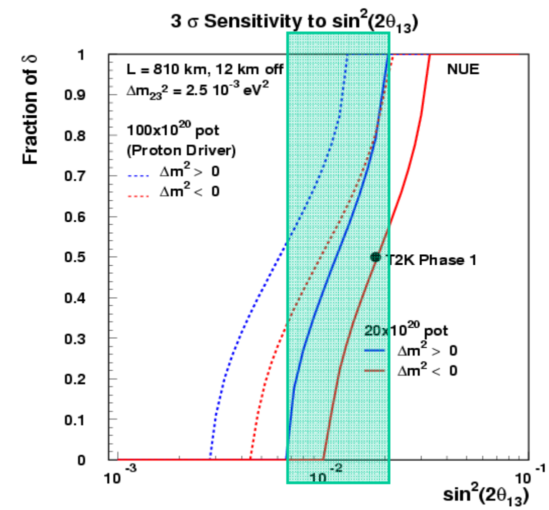
Evolution of Proton Delivery



Evolution of θ_{13} discovery limit



(from: FNAL proton driver study, to appear)



Bands show dependence on CP violation parameter δ

=located at Fermilab (NUE~Nova)

Other Activities at the lab (some very big)

- Other Neutrino:
  - FLARE: Same physics motivation as Nova, but with a liquid Argon detector
  - Cross section experiments as input to neutrino physics
    - MIPP
    - Minerva
    - Finese
    - SciBar
- Fixed Target
  - Active 120 GeV program, mostly test beams
- LHC
  - Big player in CMS
  - Level 2 Physics Center
  - LARP accelerator collaboration
- ILC
  - Major Commitment ramping up over the next few years
  - Major superconducting RF effort
- Non-HEP
  - Sloan Digital Sky Survey
  - Auger
  - Computing Grid development

Conclusions

- It's a little disorienting to see the end of the Fermilab collider program
- We are disappointed at the cancellation of the BTeV project, nevertheless
- Fermilab is poised to hold a leading position in neutrino research for the next 10-15 years.

MiniBooNE Beamline

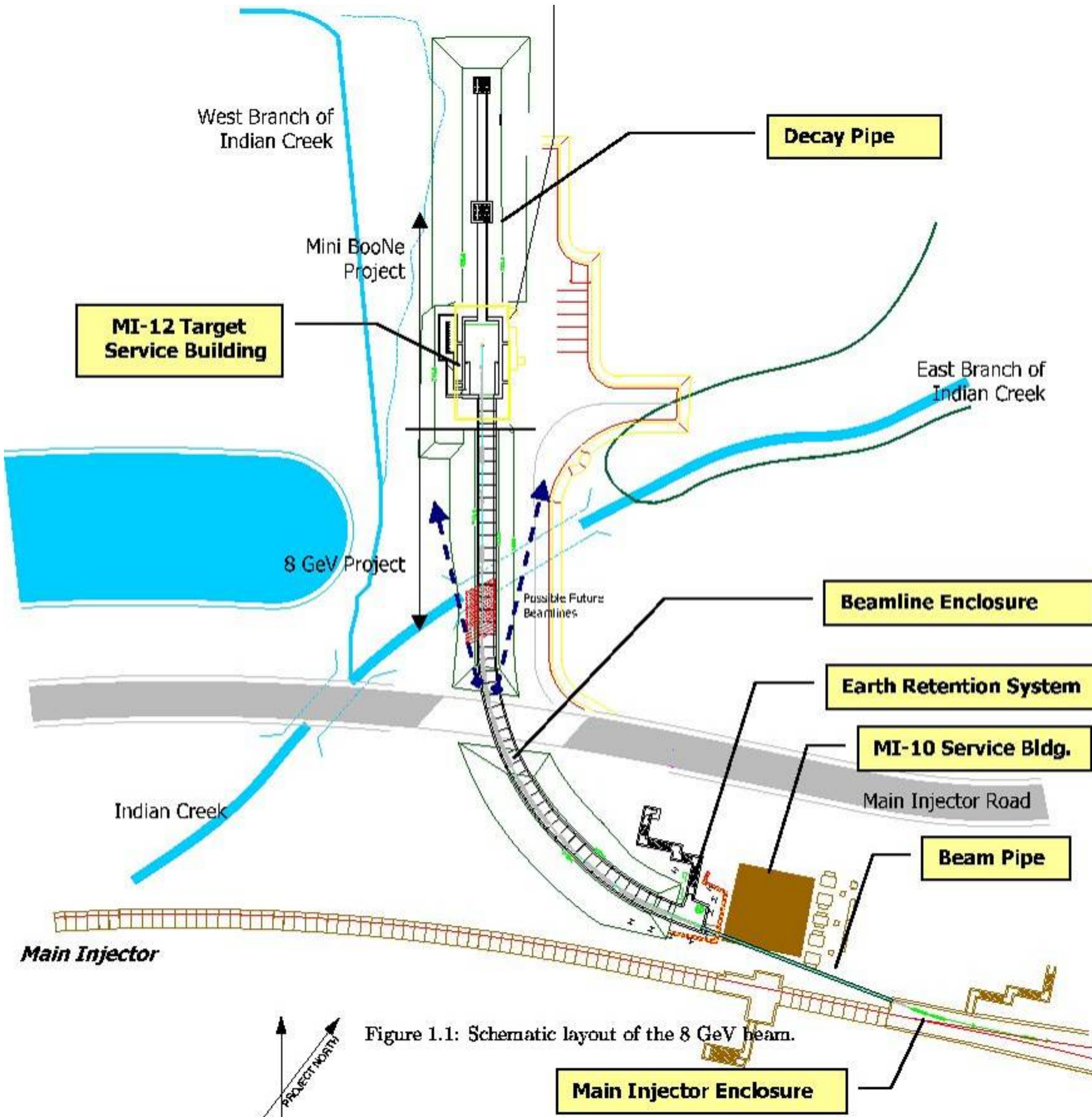


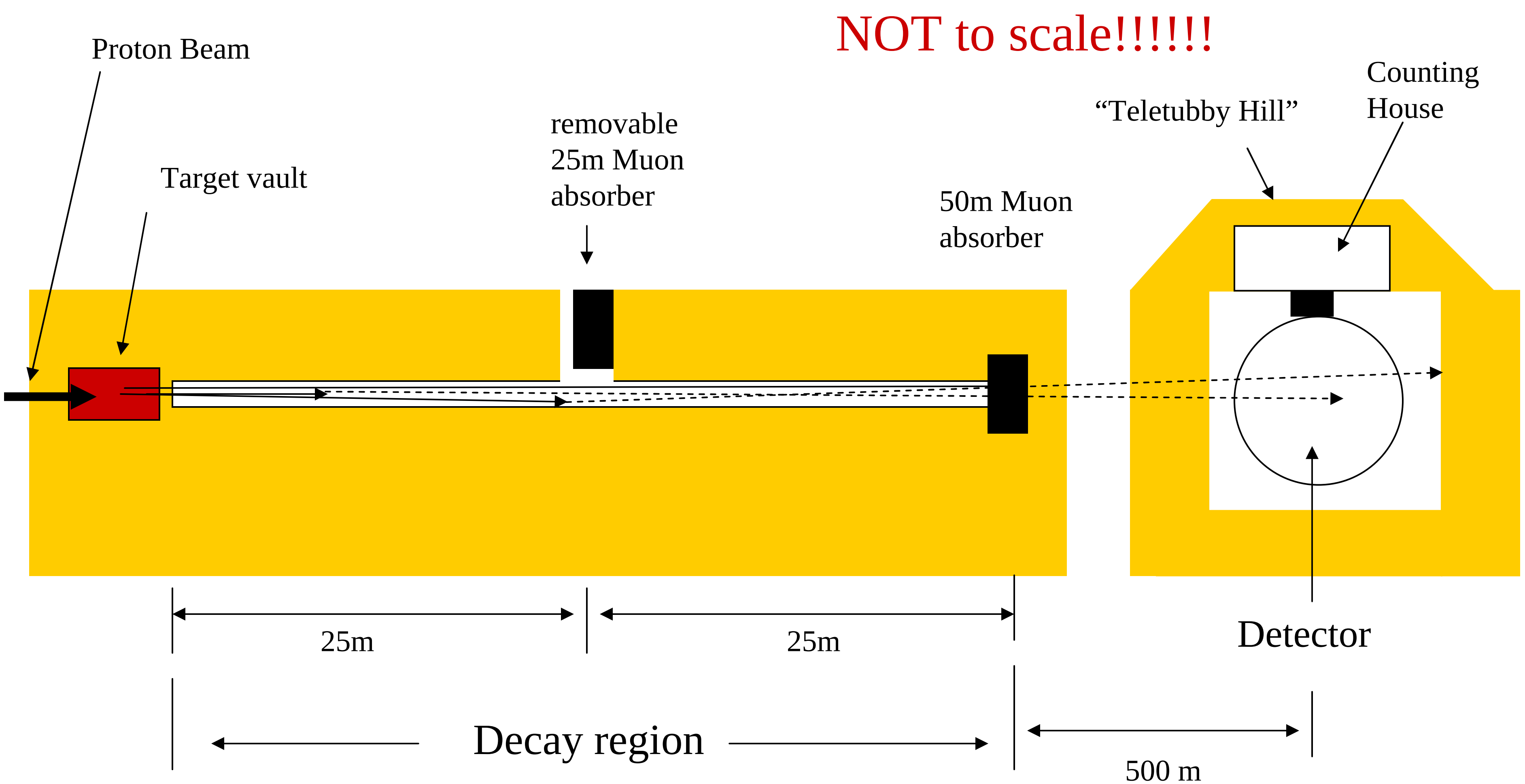
Figure 1.1: Schematic layout of the 8 GeV beam.

8GeV Beam from Booster

Neutrino Horn – Cont'd

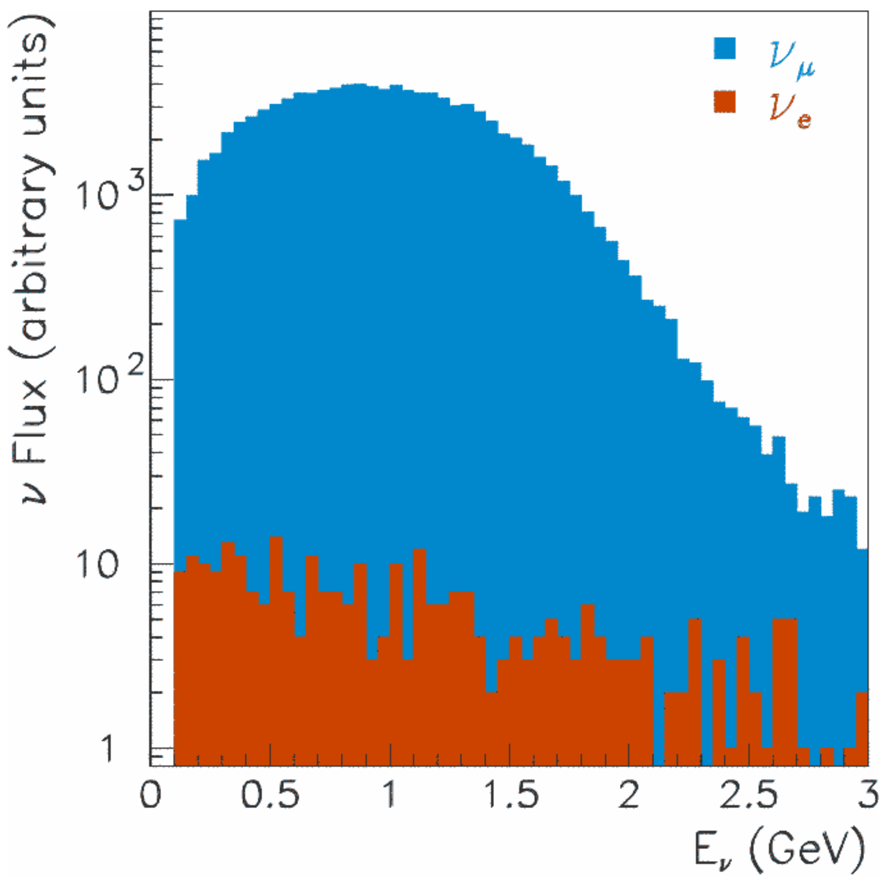
- Horn will pulse with 170 kA 150 usec pulse!
- Horn heating limits the average rep rate to 5 Hz.
- Horn fatigue is an issue.
- Under nominal MiniBooNE running conditions, it will pulse about 100 million times per year.
- Highest rate neutrino horn ever built!

MiniBooNE Secondary "Beamline"



Predicted Neutrino Flux at the Detector

The L/E ~1 m/MeV is similar to that at LSND.



-8 GeV protons on Be:

$\mathbf{p + Be \rightarrow \pi^+, K^+, K^0_L}$

-yield a high flux of ν_μ :

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \mu^+ \nu_\mu$, $K^0_L \rightarrow \pi^- \mu^+ \nu_\mu$

-with a low background of ν_e :

$\mu^+ \rightarrow e^+ \ \nu_e \ \bar{\nu}_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$, $K^0_L \rightarrow \pi^- e^+ \nu_e$

Flux estimate is important!

Nova dependence on δ